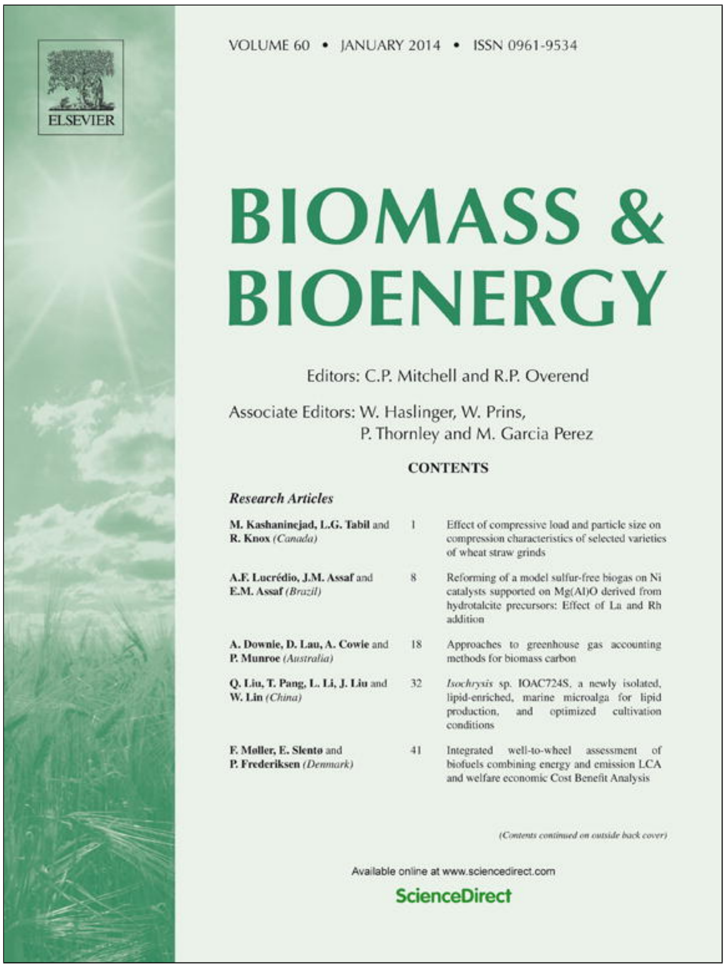
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Review

The primary forest fuel supply chain: A literature review

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ABSTRACT

This paper provides a literature review of articles on the primary forest fuel supply chain which have been published in English speaking peer-reviewed journals from 1989 to 2011. The focus is on the key issues of the transportation of primary forest fuel to heat and/or power plants: (i) transportation modes, (ii) terminal types, and (iii) forest fuel supply chain management, and provides basics on the logistically relevant characteristics of wood as feedstock such as on various feedstock assortments.

The analysed supply chains include the transshipment, storage, handling (e.g. chipping) and transportation of primary forest fuel from the place of harvest to energy conversion plant. Due to spatial distribution, low mass density, low energy density and low bulk density, the transportation of primary forest fuel is crucial for economic efficiency as well as for reduced CO_2 emissions. As a consequence of forests accessibility, road transportation (after hauling the biomass to the forest road) is the first step of the modern primary forest fuel supply chain. For longer transportation distances, rail or waterway is preferred because of lower transportation costs per volume transported and lower CO_2 emissions. We highlight that some experience exists in multimodal transport, including truck, train or ship. Intermodal transport, however, has not been studied in the past and, therefore, an outlook for the research requirements is made here.

1. Introduction

Biomass as a source of energy is increasingly gaining importance due to the worldwide rising demand for energy, scarcer fossil resources, the awareness of climate change and the environmental dilemma caused by fossil and nuclear energy systems. Focussing on Europe, the domestically available bioenergy substitutes the importing of fossil fuels from instable regions of the world and ensures energy security. Rural diversification and development is a further argument for bioenergy. Figs. 1–4

Looking at the current contribution of renewable energy sources to final energy consumption within the EU, biomass has the greatest share and steady increase within the last decade [1]. In 2009, 68.6% of the gross inland consumption of renewables in the EU 27 were produced from biomass [1]. In the majority of EU countries, the main resources for renewable energy are wood, whereof primary forest fuels (PFF) have the greatest amount [1].

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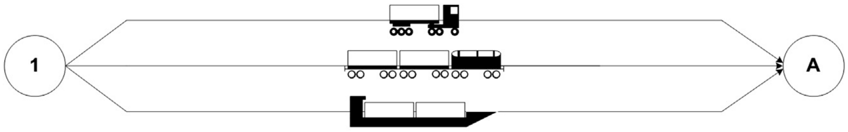

Fig. 1 – Single echelon unimodal transport (21).

The EU member states committed to realise a 20% share of renewable energy sources of the final energy consumption in 2020, leading to an increasing use of bioenergy [1,2].

Accordingly, studies proved that forests can become a major source of bioenergy, even without negative side effects, such as further deforestation [3]. Using the potentials of sustainable managed domestic woodlands is reasonable for increasing the amount of bioenergy in the energy system. Anyway, effective logistics for PFF is crucial for an economical and environmental friendly use of this energy source.

Worldwide biomass is often used in small scale applications [see e.g. Ref. [4]], but district heating systems and electricity-generating facilities have gained in importance in recent years in Europe [see e.g. Ref. [5]] as well as in other parts of the world [see e.g. Refs. [6–8]]. Due to scale effects, the costs per unit of the produced energy decrease with the size of the bioenergy conversion plant [see e.g. Refs. [9,10]]. The influence of logistics on the total costs increases with the scale of the plant [10]. Obviously, for bigger plants transportation becomes more important due to increasing feedstock draw areas and, according to Mitchell et al. [11], high transport costs limit generating capacities to typically 30 MW_{elc}. Later publications relativise that conclusion and suggest – depending on the yield density and transportation costs – optimum size up to more than 400 MW [4,12,13]. Subsequently, the Finnish plant "Alholmens Kraft" produces 240 $MW_{elc.}$ plus 60 MW of heat and 100 MW steam, burning a feedstock of approximately 45% wood based fuels, 45% peat and 10% coal [14]. However, the maximum unit size also depends on the technology used. Gasification, for example, has higher capital costs than direct combustion, but provides a higher efficiency, i.e. more electrical power is produced per unit fuel [4]. Therefore, for selecting the optimum technology and plant size, the type of biofuel and biofuel costs must also be considered [4].

PFF are not exported at a significant scale, mainly because of the relatively high transport costs [15]. Furthermore, logistics costs gain an important part on the total delivered costs of biomass [5]. It is possible to overcome this obstacle by increasing the transport density and the energy density. Therefore, pelletising and, in recent times, torrefaction of biomass gain in importance for supplying power plants from far-off sources. Accordingly, the world's largest bioenergy conversion plant Tilbury (UK) produces 750 MW_{elc}. This former coal plant is now fired entirely with biomass since 2011, and is supplied by deep sea vessels with wood pellets from North America [16].

However, transportation costs are still crucial for economic sufficiency since they represent a great amount of the total delivered costs [5,10,17–19]. Consequently, the most important cost drivers for forest fuel supply are transportation, chipping, and storage [5], with the first two processes requiring much fossil energy.

Up to now, road haulage is the dominating mode for biomass transportation. Börjesson and Gustavsson [20] argue that the energy consumption and the transport costs for longer distances could be kept rather low if the transport mode is changed, from road to rail and waterway. Similarly, Ranta and Rinne [21] point out that shifting the transportation from trucks to trains and ships would make the supply less dependent on distance and they are more environmentally friendly.

Due to the geographically dispersed source areas of biomass (see the characteristics of PFF below), an initial road transport will be necessary in most of the cases. For longer transportation distances this pre-haulage on trucks can be followed by a main haulage on trains or ships. Consequently, there is a possible need for introducing multimodal or even intermodal transport chains in the biomass sector, mainly due to the above mentioned increase in plant size and therewith the procurement areas and transport distances. Additionally, if combined heat and power (CHP) plants are located in densely populated areas according to the heat demand, truck transportation would lead to undesirable effects on the public.

The shipment of goods on two or more transportation modes (see definitions of multimodal and intermodal transport below) is gaining in importance: the transportation volumes in diverse sectors is on the rise [22] and a new research field on intermodal freight transport is emerging [23,24].

Therefore, this paper focuses on the key issues of the transport of PFF to heat and/or power plants - transportation modes, terminal types, forest fuel supply chain management – and discusses PFF characteristics and assortments. The remainder of the paper is as follows: after the basic definitions and methodology, the first chapter provides an overview on the specific characteristics of PFF affecting transportation

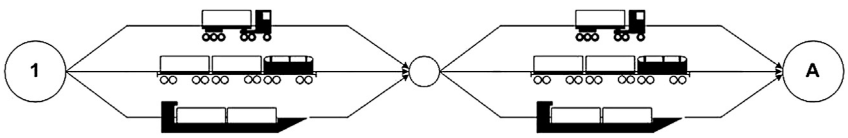

Fig. 2 – Multi echelon unimodal transport (21).

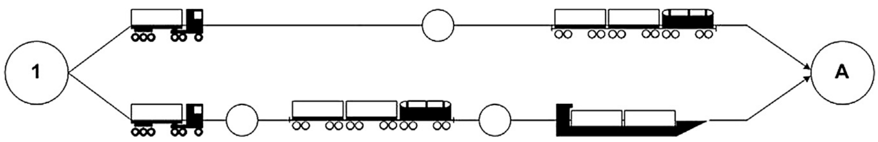

Fig. 3 – Multimodal transport (21).

issues and on energy wood assortments. The second chapter reviews transportation itself, including road, rail and waterway as well as multimodal transportation and terminals. The next chapter provides a review on supply chain management in energy wood supply chains focussing on system optimisation and simulation tools. Concluding remarks and an outlook on future research options conclude the paper.

2. Terminology

- *Bioenergy*: Energy produced from Biofuels [25]
- *Biofuel*: Fuel produced directly or indirectly from Biomass [25].
- *Biomass*: Biomass is material of biological origin [25] and, in that broad sense, forest biomass comprises the total mass of roots, stems, branches, leaves, etc. of all the species found in the forest [26]. For the bioenergy industry, only a part of this is a relevant resource, i.e. by-products of existing forest practices and special wood assortments [26].
- *(Primary) forest fuel (PFF)*: "*Forest fuel is produced directly from forest wood by a mechanical processÓ* (FAO, 2004, p. 35) and consists of traditional fuelwood, sub-standard industrial roundwood and logging residues or according to EN 14961-1:2010 [27]: "*Forest, plantation and other virgin wood*". Moreover, PFF are solid biofuels, also referred as energy wood.
- *Bioenergy conversion plant*: Place where biofuel is converted into energy (electricity and/or heat and/or cooling). For PFF combustion is the process mainly used from a very small scale up to industrial plants.
- *Net calorific value*: Quantity of heat released during the complete combustion at standard conditions when the formed water remains water vapour; the old term is a lower heating value [25].
- *Single echelon unimodal transport*: no transshipment takes place (e.g. logs from forest landing to the plant directly via log trucks).
- *Multi echelon unimodal transport* includes a transshipment operation, where the means of transport are changed, the mode remains unchanged (e.g. prehaulage on forest roads with all-wheel drive trucks to simple terminals and main haulage on country roads by truck-and-trailer).
- *Multimodal transport*: the mode (i.e. road, rail, waterway) changes (e.g. bundles, produced in the forest, are transported on trucks to a train terminal, and then transshipped on trains and delivered to a CHP plant).
- *Intermodal transport*: use of one loading unit on two or more means and modes of transport [22,24].

3. Methodology

The scientific literature was reviewed to illustrate primary forest fuel supply chains, and, especially, to answer the question of whether and to what extent multimodal or intermodal transportation systems were studied. The review focused on peer-reviewed journals in English, since they are a widespread source for researchers worldwide. The publication dates range from 1989 to 2011. The keyword search was carried out using the following databases and library services (in alphabetic order): Emerald (www.emeraldinsight.com), Sciencedirect/Elsevier (http://www.sciencedirect.com), Scopus (www.scopus.com), Springer (www.springerlink.com), Wiley (www.wiley.com). Additionally, we searched for relevant papers by reviewing the reference lists of the publications found by the keyword search. Altogether, we located references to more than 250 papers, but only a part met the criteria for inclusion. Within the field of forestry, an appreciable number of scientific studies were published, of which only those studies with a focus on PFF transport were included. Papers that exclusively focus on non-forest biomass resources (e.g. straw, switchgrass) were excluded, because the supply systems often differ from those of forest biomass. Some topics are not well illustrated in English-speaking peer-reviewed journals; in such cases, we resorted to other scientific sources.

3.1. General characteristics of papers citied

The most frequent journal where relevant papers were found was Biomass and Bioenergy (51 papers). Several papers were found in the Scandinavian Journal of Forest Research (10 papers), the European Journal of Operational Research (8 papers) and the International Journal of Forest Engineering (5 papers).

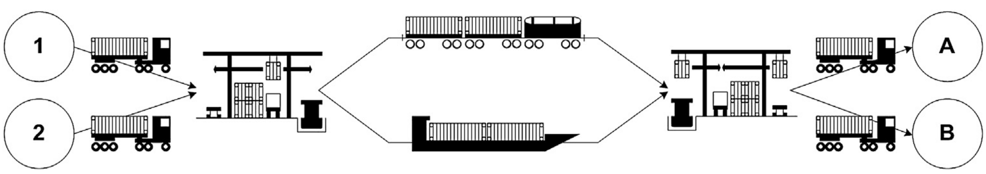

Fig. 4 – Intermodal transport (21).

Additionally, a great part of the relevant papers were found distributed to a greater number of journals, which can be roughly allocated to the fields of forestry, energy (bioenergy), climate change and environment, or operational research, respectively.

Looking at the time horizon, regarding when the work was published, it can be seen that the overall topic arises in the 1990s, while the number of publications increased reasonably around 2005.

Nearly all of the relevant research work addresses either North America or Europe, whereof the most studies originate from Northern Europe, where PFF have been used for bioenergy for decades. Sweden and Finland have been the most relevant ones in PFF supply chain research with nearly 20 published peer-reviewed studies each that are included here. There is also a relevant number of studies from Central Europe, primarily Austria and Southern Europe (Italy, Spain and Greece). Furthermore, 11 included studies focus on the US and 6 on Canada. However, some of the reviewed studies do not have a geographical focus. As shown later in this review, mostly road transport is considered. On the other hand, train and especially ship transportation are underrepresented.

There are only a few scientific publications on the multimodal transport of PFF, while publications on intermodal transport from forest to energy conversion plant are absent. North American scientists dealing with the energy use of biomass have mainly considered agricultural biomass (e.g. crops, corn stover, switchgrass or cotton stalks). Furthermore, the North American literature often considers biomass for producing secondary biofuels, while the European literature on PFF observes supply chains for combustion plants, producing power, heat and cooling.

4. Primary forest fuel: characteristics and assortments

Biomass as a source for energy has several noteworthy characteristics that considerably affect the supply chain. Forest fuel is a low value commodity and transport costs contribute to an extensive amount on the total procurement costs [28]. Hence, logistic costs for fuel supply make producing electricity from biomass more expensive than from other sources, such as coal and gas [17]. Wooden biomass generally has a relatively low density (cell structure of wood) and the heating value of biomass is relatively low compared with fossil fuels. The bulk density of the transported material is low, depending on the assortment of PFF (e.g. small roundwood/chips/loose residues). The bulk density depends on the wood species, specific density, particle size distribution, particle shapes and orientation, moisture content as well as the applied pressure when loaded. Methods of compacting and comminuting change the bulk density [29]. Increasing the bulk density and therewith the energy density, obviously increases the efficiency of any transport.

Harvested wood has a high moisture content and, therefore, a low heating value, but when fed into the conversion process, the moisture content of forest fuel should be as low as possible. Due to moisture, the weight of the transported material increases and so do the costs [e.g. Refs. [19,28]]. The high moisture content of feedstock leads to a higher forest fuel demand in terms of the supplied volume, increases the number of shipments needed and the volume of ash to be deposited at the end of the conversion process [30]. Talbot and Suadicani [28] identify the moisture content as the most important controllable factor in determining transport efficiency.

In supply chains, supply shortages are usually buffered by means of stored material, leading to so-called hidden inventory costs due to material deterioration [31]. Contrarily, storing woody biomass properly for several months increases the net calorific value due to natural drying, however biodegradation leads to dry matter losses [30]. The efficiency of biomass transport improves with drying at the early stages in the supply chain [32]. We differentiate between (i) natural drying and (ii) technical drying. The drawback of the first one is that the effect of the drying is hardly predictable or controllable because the process of drying depends not only on the seasons, but also on the weather and environmental conditions. Natural drying takes place during storage and transport [33].

Water uptake, mainly during rain, impairs successful drying, while covering roundwood piles may counteract the problem [34–36]. Additionally, the process of drying also depends on the type of stored material (whole trees with leafs and branches, delimbed and (partly) debarked trees, compacted or uncompacted) as well as the storing location [34–37]. Debarking or partial debarking of both hard- and softwood species helps to effectively reduce moisture during storage [38]. Natural drying is most efficient during the spring and summer, covering the piles helps to maintain the lower moisture content during the winter [38]. Whereas technical drying ensures PFF with the desired moisture content, it introduces additional processes and costs to the supply chain.

Biomass resources, i.e. forests, have a scattered geographical distribution, this makes harvesting, transport and storage demanding [17,39,40]. Physical constraints, such as steep slopes, wet terrain or missing (unsuitable) forest roads can make harvesting actions impossible and reduce the available biomass potential. Furthermore, biomass assortments can at least partly be used for diverse applications (e.g. in forest based industry as production feedstock) and, therefore, competition on conflicting material uses have to be considered when estimating the biomass potential [6,39]. Additionally, forest land owners' decisions as to whether to harvest biomass or not depend not only on economic factors and those decisions sometimes dramatically reduce the so-called market available biomass potential of a region [39]. Lundmark [7] studied the competition for forest-based biomass in Sweden and concluded that it is economically feasible to extract in total 21 TWh of harvesting residues from Swedish forests (this is an additional 12 TWh compared with current use), before it becomes more profitable to use roundwood for energy purposes, resulting in intensified competition between the forest industry and the energy sector.

Seasonality is more pronounced for agricultural biomass than for PFF [33,41], but due to varying weather conditions during the year the harvesting periods are limited. For example, in Austria many forest roads cannot bear loaded trucks until snowmelt, after heavy snowfalls, or after heavy rainfall [39,42]. Accordingly, Gronalt and Rauch [39] present forest fuel supply curves showing the seasonality of the supply on a monthly basis. Based on different supply conditions, they split the federal state of Salzburg (Austria) in two main supply regions, the Alps and the Pre-Alps. Successful operation of bioenergy conversion plants requires a constant supply with heating material throughout the year [40], but for district heating the demand is the highest in the winter [42]. Therefore, asynchronous supply and demand curves of forest fuel have to be taken into account when planning the supply of an energy plant. PFF originate in small quantities from various forest sites and are supplied to a few bigger plants. Here, terminals can serve as transfer sites and allow for a more constant supply [42].

Forest fuel supply is threatened by several specific risks, which are seldom considered explicitly in procurement cost calculations. For Austrian CHP plants, raw material competition due to production restrictions, sudden undersupply in consequence of natural disturbances and the biodegradation of fuel were reported as the main forest fuel supply chain risks [30]. In addition, specific weather conditions, such as rain and snow, can delay forest fuel logging operations and are the main reason for the large variance in the daily quanta of the supplied fuel [43].

4.1. *Primary forest fuel assortments*

Referring to the standard EN 14961-1:2010 [27], biofuels are classified according to their origin; the standard classifies “forest, plantation and other virgin wood” (PFF) which is divided into (1) whole-trees with roots, (2) whole-trees without roots, (3) stemwood, (4) forest residues, (5) stumps and roots, (6) bark, (7) wood from parks, orchards, etc., and (8) intermixtures of 1–7. However, for our purpose we focus on forest, plantation and other virgin wood including all the subclasses and term it primary forest fuel (PFF) because this seems to be more adequate according to the published literature. The assortment determines a main part of the transportation costs, since for example the bulk density can be doubled if the energy wood is comminuted, i.e. chipped, or compressed, i.e. bundled [21,44].

The following assortments are described: (1) loose/uncompressed/uncomminuted forest residues, including tops, branches, broken stemwood and off-cuts (2) small roundwood, low-quality logs and whole-trees, (3) stumps and roots, (4) bundles, (5) chips and (6) bark.

4.1.1. *Forest residues*

Forest residues (also called slashes or forest arisings) are a side-product of conventional timber harvesting and available at the forest site at time the trees are processed (final cutting or thinning, respectively). Regardless of the topography and soil conditions as well as the harvesting process and the harvesting machinery used – this is not entirely covered within this review – the residues must be made available at the forest landing, where trucks can be loaded. The main disadvantage of loose residues is the low bulk density and hence when the material is loaded onto a truck it is difficult to reach the payload [29,45]. The advantage of transporting loose residue is to save investment costs for chipper or bundler, respectively [29,45]. In case of delivering uncomminuted material, a stationary chipper at the plant site provides a higher throughput at reduced costs compared with mobile chippers, and therewith higher transportation costs can be compensated sometimes [45].

Furthermore, logistics is easier because the truck for loose material can move independently from a chipper-unit and delays related to the chipping at landings can be disregarded [21]. Transporting loose residues is reported from Northern Europe [21] as well as Central Europe [45]. In Central Europe, the usage of logging residues is limited to whole-tree logging systems using a cable yarder, where delimbing takes place at landings so that forest residues are concentrated at the forest roadside [39]. In Sweden, the transport of loose residues contributes to about 10% of the whole PFF transport volume [21]. In Finland, the average transport costs for loose forest residues are considerably higher than those for compressed or comminuted material, hence the transport of loose forest residues is suitable only when transport distances are short [21]. For distances less than 40 km, the transport of loose residues is less cost intense as the transport of comminuted residues if the residues were accumulated at the landing after cable yarder harvest and delivered costs included all the stages from landing to the bioenergy conversion plant [45].

Focussing on Finland, the transport of loose forest residues is mostly suitable for large-scale plants with a stationary chipper, whereas the supply with forest chips is more suitable for small scale combustion units [21].

4.1.2. *Small roundwood, low quality logs and whole trees*

The transport of whole-trees with attached branches resembles the transport of forest residues, but with a slightly higher bulk density due to stemwood parts. In the so-called “tree section method”, stems are transported with attached branches (or stem section with branches) to pulp mills and branches are separated as an energy product. It is common in some Nordic countries [44,46,47].

If delimbed and cross cut, stemwood – including both, small diameter trees and low quality logs – is transported, and the bulk density is much higher and transport activities are similar to timber or pulpwood transportation. After forwarding, the trees are either chipped on the roadside or at the conversion plant.

Small roundwood is a source for pulpwood as well as for forest fuel. A comparison of the removable volumes of energywood and pulpwood, and their respective gross values in stands of young birch thinnings was carried out in Sweden [48]. The authors concluded that the production of forest fuel is economically better than the production of pulpwood in thinnings of young stands.

Studying the profitability of using small roundwood from thinnings for bioenergy in Finland, it was found that energy wood thinning was economical if a volume of at least 42 m^3 per ha has been removed. Moreover, government subsidies play an important role in using small roundwood [49].

Procurement costs of whole tree chips from early thinnings were compared for two Finnish supply chains: (i) chipping at the roadside landing or (ii) chipping at the terminal. The direct transport distance from the forest to the terminal or the bioenergy conversion plant was 40 km; the distance from the terminal to the plant was 10 km. The supply chain with chipping at the roadside landing was considerably cheaper. Contrary, chipping costs were lower at the terminal, but not enough to cover the higher transport costs of loose material and additional handling costs at the terminal [50].

4.1.3. *Stumps and roots*

After clearcutting, stumps are lifted up and split into two or four parts during or after the logging. Stumps can be left in the forest to dry for over a year; during the drying soil and sand drop off. According to applied studies, harvestable dry mass of coniferous stumps with roots >5 cm was 23–25% of the trunk mass and gained energy of 1 ha removed stumps varied between 140 and 250 MWh [51].

Stump removal is not only done to gain bioenergy, but also due to silvicultural reasons [51]. Stump removal is also applied in poplar plantations in Southern Europe, where the intent is to clean the field and land owners remunerate the operator [52].

Walmsley and Godbold [53] mention several benefits of stump harvesting: supply with forest fuel, and hence a substitution of fossil fuels, additional revenues for forest owners, reduction of infection risk with *Heterobasidion* sp. and improved site preparation. At the same time, undesirable environmental impacts can occur, for example reduced forest soil carbon storage, nutrient depletion, removal of soil organic matter, habitat loss, increased erosion or soil compaction [53].

In contrast to small-diameter trees and logging residues, which are mainly chipped at roadside landings, practically all stumps are comminuted either at the plant or at terminals with heavy, mainly stationary crushers [54,55]. For transporting stumps, special trucks are needed and economical transport distances are short [54]. A key factor for cost efficiency is the amount of removed mass per hectare [51].

Stump removal on forest sites is important in Northern Europe, but volumes are declining Practical guidelines for stump removal and restrictions of such activities are available for a few countries, e.g. Finland, Sweden or UK. However, in many countries stump removal on forest sites has actually no relevance, mainly because of ecological impacts and high extraction costs.

4.1.4. *Bundles*

Bundling, i.e. compacting in a cylindrical shape, is carried out with logging residues, such as tops and branches, but is also capable of handling small trees [56]. Bundles can be transported on regular log trucks since they have the shape of wood logs; due to their shape bundles are also called "compact residue logs" (CRLs) [57] or "composite residue logs" [58]. Bundles have a higher bulk density than loose residues, which increases the payload. In contrast to wood chips, bundles can be stored for a longer period without reasonable mass loss [36,59]. Both, drying before and after bundling is possible [60].

Bundling represents an additional procedure in the supply chain with additional costs, but it increases bulk density, reduces transport costs, and the comminution with stationary chippers at the target location is more efficient [60].

Besides a two-machine-system with separated felling and bundling, there are also bundle-harvesters with a compacting device on the vehicle [61]. In Nordic countries, bundling is done on terrain at the stump site [56,61–63], whereas in Alpine regions the bundler always works at a landing by the roadside [57]. When timber is extracted by cable yarders, the logging residues are accumulated at the roadside and are capable of bundling machinery. An advantage under mountainous conditions is that the space needed for a bundler is much less than for chipper and truck, a disadvantage is the lower throughput [45]. In contrast to chipping directly into trucks, the independent operation of bundler and log trucks reduces organisational problems [45]. However, in contrast to Nordic countries, bundling is rarely used in Central Europe.

Analysing Swedish bundle-systems, Johansson et al. [63] showed that delivery costs are lower at any distance compared with wood chip systems; the same was shown for Finland [21]. In contrast, Spinelli et al. [45] report that under Central European conditions delivered costs are higher for a bundle-system than for transporting loose residues or comminuted residues when observing road transport up to 80 km. Similar outcomes can be found by Lindroos et al. [59] for Canadian conditions, where the bundle system is most expensive up to 100 km.

Bundles play an important role in the forest fuel supply chain in Nordic countries, for example the 240 MW_{elc}.power plant "Alholmens Kraft" consumes 1 TWh of wood fuel annually, whereof 0.3 TWh are logging residues bundles [56].

Harvesting both pulpwood and fuelwood concurrently is practised as well as to bundle them together in the same bundle; we term this technology combined bundle [47,61,64].

4.1.5. *Chips*

Depending on the comminution technology, chips vary in size and shape. Crushers (shredders) hammer pieces of wood apart and produce a material which is coarse and inhomogeneous in size [65]. Chippers cut the wood with knives and produce more uniform pieces that are slick and easy to convey [65]. The EN 14961-1 calls the first one hug fuel, the second one wood chip fuel gives specifications for both [27]. Obviously, the type of material used for combustion must fit to the individual process. Particle size and size distribution as well as moisture content are the main characteristics for combustion processes. Chipped forest residues usually include bark, needles or leaf and are sometimes contaminated with sand.

For long-distance transport, chips have the disadvantages of a relatively low bulk density and vulnerability to fungi due to moisture content and large specific surface [32]. Storage of wet wood chips can induce biological processes of degradation connected with considerable dry matter loss of the feedstock. Furthermore, produced fungal spores are a health risk to employees working with wood chips [66]. Biological activity can lead to heat development with the risk of self-ignition [66]. A moisture content of forest chips of less than 30% reduces dry matter loss significantly and enables long-term storability [67].

Chippers might be classified according to the technology (disk and drum chippers are primarily used) and according to the performance. For our purpose, however, we distinguish between a mobile chipper and stationary chipper. The first one can move to chipping sites in the forest or simple terminals; smaller chippers are tractor powered, while bigger chippers are self-propelled and mounted on trucks, and some have integral loaders [68]. Stationary chippers are located at larger bioenergy conversion plants or industrial sites but also at terminals. Stationary chippers have generally higher capacities thereby making chipping more efficient. Chipping at plants or terminals is also done with powerful mobile chippers if no stationary chipper is on hand. The differences between terrain chipping, roadside chipping and chipping at the terminal or bioenergy conversion plant are illustrated in Table 1.

4.1.6. Bark

Bark as a forest fuel is commonly transported as part of another product, i.e. saw logs or pulp logs [44]. After debarking, the bark is either transported internally (e.g. to the heating plant on the site) or by road and rail. Assuming that most of the bark for energy use is transported only very short distances, vehicles (wheel loaders) and conveyor belts are reasonable technologies. However, there is an economical penalty if the utilisation of bark is not at the same plant due to the double transport [44]. Other assortments can also contain some amount of bark. The bark percentage of wood chips is a quality factor, since the bark's energy density is lower than that of stemwood and the ash content is higher, which is a fact that increases maintenance costs [38].

5. Technical forest-fuel procurement systems

To feed woody material into a combustion plant, comminution is necessary. The allocation of the comminution process determines the form of the transported material and is, therefore, crucial for the whole supply system [50]. Different authors have made classifications of PFF supply chains. However, we classify the supply chains on the basis of the assortment to be transported and the place where comminution is carried out (Table 1). Most of the supply chains used in practice can be arranged within that classification scheme, but the reader could find a specific case, which can hardly be represented within that scheme.

5.1. *Terrain chipping*

Forest residues are chipped into a container at the forest stand and hauled to the landing either by a single machine (chip harvester) or a combination of a chip harvester and a chip-bin forwarder [69,70]. Between felling and chipping, the material can be left in the stand (on the strip road) for drying [69,70]. At the forest road the chips are transhipped into an exchangeable truck-container for road transportation. In Denmark, terrain chipping is common [69,70] and, in Italy, terrain chipping has been reported from plain site plantations [68]. A study on terrain chipping in spruce stands in Denmark compares several treatments: (i) motormanual felling and whole-tree chipping, (ii) feller-buncher and whole-tree chipping, (iii) harvester felling and whole-tree chipping and (iv) integrated harvesting of saw logs and forest residues for terrain chipping [70]. The study indicates costs and incomes and, additionally, chip quality and damage rates on shelter trees; the economically best alternative proved to be the feller-buncher-system [70]. In addition, it was found that the productivity strongly depends on the ease of feeding [70].

A simulation was carried out to examine whether a chip harvester as a single machine or a combination of a chip harvester and a chip-bin forwarder is the most economically favourable solution [69]. Low turnaround times and enlarging bin size were favourable for the single machine system, while increased chipper productivity conduced to the two-machine system, irrespective of bin size [69]. Analyses of supply chains for forest chips in Finland from 2004 to 2006 proved that terrain chipping was used only to a very small extent [55].

Table 1 – Classification of technical forest-fuel procurement systems.

No	Place of comminution or compacting				Transported assortment	
	Forest stand	Forest road	Terminal	Plant	Transport 1	Transport 2
1	Chipping				Chips	
2		Chipping			Chips	
3			Chipping		Loose material	Chips
4				Chipping	Loose material	
5	Bundling[a]	Bundling[b]	Chipping		Bundles	Chips
6	Bundling[a]	Bundling[b]		Chipping	Bundles	
7	Bundling[a]			Chipping	Combined bundles	
8				Chipping	Roundwood or stems with branches and/or bark	

1. Chipping at stand/terrain.
2. Chipping at roadside landing after hauling loose material (forest residues, small roundwood and low-quality roundwood).
3. Chipping at the terminal after transport of loose forest residues, stumps, small roundwood and low-quality roundwood.
4. Chipping at the bioenergy conversion plant after transport of loose forest residues, stumps, small roundwood and low-quality roundwood.
5. Bundling (i) on terrain (ii) at the forest landing of forest residues and small roundwood and chipping at a terminal.
6. Bundling (i) on terrain (ii) at the forest landing of forest residues and small roundwood and chipping at plant.
7. Integrated harvesting and transportation of pulpwood and energy wood in the same bundle (combined bundle).
8. Transportation of energy wood as part of another product 8.1. Bark on roundwood 8.2. Stems with attached branches (or stem section with branches) there branches are separated as energy products at the plant.

[a] Bundling at the terrain (Nordic method).

[b] Bundling at the forest road after cable yarding (Central European method).

5.2. *Chipping at the roadside landing*

Here, chipping can be performed either by a separate chipper (transportation by chip trucks) or by an integrated chipper-chip truck [55].

In-woods chipping (as a US synonym of chipping at the roadside landing) of unmerchantable stems is near the break-even point under US-conditions [71]. Chipping of branches, tops, small and broken roundwood, etc. directly at the forest road is reported in many studies in Northern Europe [21,55], Central and Southern Europe [45,72], North America and Japan [73,74]. About 70% of the annual forest biomass production in Finland is chipped at the forest road [21]. In Austria, approx. 2/3 of the volume of PFF is chipped directly onto trucks at the forest landing and transported immediately to the plants [75]. Direct chipping into trucks results in an interdependency of the chipping device and trucks with any delay affecting the overall productivity and procurement costs. Possible solutions are interrupted work chains or a pre-concentration of the material at a central landing. When a chipper and truck must be collocated in mountainous conditions this can be difficult [72]. If loading is separated from chipping, trucks are usually equipped with a loading crane [21].

5.3. *Chipping at the terminal*

Interposing a terminal in the upstream transport of PFF from the forest to a bioenergy conversion plant splits the supply chain into transport 1 and transport 2 as well as transshipment activities. Transport 1 and 2 can be performed with different transportation modes. While transport 1 will almost always use roads, transport 2 might also use rail or waterways. If the terminal is the point of comminution, the assortments for transport 1 are (i) loose material (forest residues, small roundwood and low-quality roundwood) or (ii) bundles. A stationary chipper has a higher productivity than a mobile chipper, set-up times are shorter and the chip quality is higher and, because of economy of scale, it is more cost-effective than chipping at a roadside landing [76]. In case of transporting loose fuelwood, the transport volume is very high due to its low bulk density, this is the main disadvantage of this system [72].

5.4. *Chipping at the bioenergy conversion plant*

For this method, the forest residues, small roundwood and low-quality roundwood are either transported loose by container trucks or bundled with log trucks [55] [77]. A local adaptation of the tree section method is reported from the Italian Alps, where whole trees are logged, cut into sections while loading and undelimbed tree sections are transported to a bioenergy conversion plant [78]. After comminution, the further intern transport is done by wheel loaders or conveyors. Similarly to stationary chippers at terminals, a stationary chipper at a bioenergy conversion plant has some important advantages. In addition, at industrial sites, a chipper may also be used to produce chips for pulp or panel production. Stumps are comminuted with heavy, stationary crushers [55]. In Finland, approx. 80% of total PFF are crushed at plants, 20% at terminals [55].

5.5. *Bundling and chipping at a terminal or bioenergy conversion plant*

Bundles of forest residues can be used for a supply chain where the chipping is done at a power plant or terminal. Chipping at the customer is cheaper, but it is necessary to use powerful chippers to chip bundles. Furthermore, it is reported that the transport of bundles can cause traffic hazards due to wood pieces falling off [63].

5.6. *Combined bundles*

Combined bundles are transported to pulp mills using standard timber trucks. These bundles include both pulpwood and forest residues with small diameter stems and are fed into the debarking process and afterwards the pulpwood is separated. This supply chain provides PFF at industrial sites without placing the raw-material supply for the pulp industry at risk [64].

5.7. *Transport of energy wood as part of another product*

For the transport of energy wood as part of another product, bark on roundwood represents the most common example [44]. The "tree section method" is used in Scandinavia. In this system stems with attached branches (or stem section with branches) are loaded onto trucks and transported to pulp mills, where branches (and bark) are separated as energy product [44,46,47].

6. Transport

The point of reference of a bioenergy supply chain is the facility where energy conversion takes place. Therefore, an upstream supply chain – which is reviewed within this paper – and a downstream supply chain providing energy products can be defined [79]. Energy products produced of solid biomass include electricity, heat and – in the case of trigeneration – also cooling. For the biomass upstream supply chain, three general transport systems are available: (1) Transport in point-of-origin form, which means tops, branches, off-cuts, but this is only viable for short transport distances; (2) Transport in reduced particle size, which means the transport of chips; (3) Transport as part of an other product, which includes bark on roundwood as the most common example, as well as the "tree section method" [44]. Angus-Hankin et al. [44] in 1995 neither classify bundles nor combined bundles, but already mentioned bundling as developing technology. PFF are always comminuted before entering the combustion process. The place of comminution within the supply chain and the specifications of the produced fuel have the main influence on logistics and as well as on the economic success of energy conversion plants [65].

6.1. *Transport modes for primary forest fuel*

Total transport costs can be sub-divided into (i) distance variable costs, which directly depend on the transport distance, and (ii) time dependent costs [39], also called distance fixed costs [19], which include inter alia the costs of loading and unloading and are independent of the transport distance. Time dependent costs will vary based on the specific form of biomass to a far greater extent than distance variable costs [19]. The impact of time dependent costs on the total costs decreases with increasing transport distance [19]. Searcy et al. [19] compared truck, train and ship transport of corn stover, straw and PFF and clearly showed that distance variable costs are the highest for truck transport and the lowest for ship transport.

Truck transport for biomass "*is generally applied for relatively short distances (<100 km), when flexibility is required because multiple (small) production sites have to be accessed, or when train and ship infrastructure is absent*" [32]. Accordingly, as places for collecting biomass are – in contrast to other sources of energy – widespread, road transport is often the only potential mode for collection [80]. Loading and unloading times for energy wood in Finland showed a large fluctuation range. The unloading of chips is considerably faster than for bundles; the unloading of loose residues or stumps is the most time intense lasting two times longer compared to chips [21].

Train transport is favourable for overland distances exceeding 100 km and ship transport is applied for long distances [32]. At the same time, ship transport has the highest time dependent costs and, therefore, using the waterway is only economic over long distances, exceeding 800 km [19]. Nevertheless, plenty of factors (e.g. mode of transport, physical conditions (unchipped, chipped or baled), moisture content, or plant size) influence the economical transport distance and thus cannot be fixed in general [6,39].

6.1.1. *Road*

The typical locations of biomass resources, i.e. mainly forests, have a scattered geographical distribution and available transport infrastructure usually restricts the potential transport modes to road transport for the collection of the fuel [5]. Subsequently, in Norway, only roads are used for the transport from the forest to the energy conversion plant as has been proved by the analyses of potential PFF supply systems [15]. While for short chip transport even farm tractors are used, greater distances are travelled by trucks and for distances over 50 km, truck-and-trailer units are preferred [68]. Furthermore, container trucks are less popular because their tare weights limit the payload [68].

Comparing road transport costs for loose material, chips and bundles it was found that for all distances (10–150 km) of truck transport, bundles where the cheapest and loose material the most expensive alternative [21]. Johansson et al. [63] describe advantages and disadvantages of the transport and handling of bundled energy wood (forest residues) as an alternative to wood chips. The study shows that bundles are cheaper to transport than chips in road transport containers for all transport distances. For dry material, the maximum load is limited by the volume of the material, whereas the weight limits the maximum load for chips and bundles with a moisture content of 40.9% and 44.7%, respectively [63]. Accordingly, for air-dry wood chips, the limiting factor is the volume of the load, while for wet chips the maximum weight limits the load. Higher tare weight (as for the truck-trailer-combination with containers) lowers the maximum payload [28].

Analyses of (i) a container based transport system (2 containers on a rigid truck with a drawbar trailer) and (ii) a bulk trailer system (articulated truck with a full tri-axled walking floor trailer) for transporting chipped PFF observed that due to the higher payload, the bulk trailer system is economically preferable, especially with increasing distances. In contrast, trucks with drawbar trailers allowed for better accessibility on forest roads [28]. Increasing the bulk density of the load towards the maximum payload (legal restrictions for trucks) can be done with mechanical force (e.g. the ejector of a belt conveyer can increase the load density). It was proved that raising and dropping the front end of a container increased the bulk density over 5% [28].

Short distance road transport of loose material using a roll-off trucking system (exchangeable containers) was studied under mountainous conditions in northern California [81]. The roll-off system is a straight frame truck configuration in which a 30.6 m^3 container is rolled on and off using a truck-mounted winch. The woody material consisted of vegetation (including trees and shrubs), which was removed manually in so-called fuelbreaks to prevent the spread of forest fires. Due to slow travelling speeds and the low slash weight being hauled, the roll-off trucking system should be used primarily for short hauling distances since trucking costs increase significantly with small increases in hauling distance. The material was hauled to simple terminals near the forest, where it was comminuted before further transport [81].

The transport costs of PFF also depend on backhauling options. Fleischmann et al. [82] reviewed the literature about backhauling, but disregarded the fields of forestry and bioenergy. Palander et al. [83] applied a model based on linear programming on energy wood networks minimising empty trips in combination with an optimisation of backhauling. Empty-route minimisation seemed to give profitable return routes and the backhauling model seemed to perform well. Moreover, with the help of a simulation model impacts of interenterprise collaboration and backhauling on the wood supply in Finland were estimated and especially the implementation of both led to a significant increase in the economic efficiency (e.g. reduction of transport costs, reduction of roadside inventory, shorter transport distances [84]). Carlsson and Rönnqvist [85] developed an LP model to solve the tactical problem of backhauling in forest transport in Sweden.

An Internet-based, general-purpose logistics control system, using mobile data terminals in forest fuel chipping and transport helps reducing costs, especially if operating areas are large and complex structured [86].

Analyses of diesel fuel consumption of road based forest fuel systems proved site-specific factors (e.g. location, harvesting technology) and road transport distances as the main cost issues [87]. Accordingly, for the state of New Hampshire (USA), a rise in diesel price of $1 per litre would lead to an increase of wood chip price of $5.59 per tonne. Using a Mixed Integer Linear Programming (MILP) model and the state of Austria as a case study, results pinpoint that a 20% increase of energy costs results in a forest fuel procurement cost increase of 7% and domestic waterways will gain a 4% share of modal split from road transport [75].

Basically, all the research addressing road transport considers single echelon unimodal transport. If the travel distance on roads is split into pre and main haulage with different road vehicles it is defined as multi echelon road transport. Transport on rail and waterway has usually a previous road transport and thus these transport chains are mainly multimodal.

6.1.2. *Rail*

These days, the rail transport grows in importance due to cost efficiency, longer distances to be travelled, and traffic problems in urban agglomerations. Furthermore, rail transportation using electricity from renewable sources is more energy efficient, has a lower global warming potential and negative impacts on the environment are reduced compared with other transport scenarios (Lindholm and Berg [88]).

The use of both, truck and train, leads to additional work phases (extra unloading and loading) and the resulting costs cannot be fully compensated by the lower transport costs at a 50 km distance, but at 200 km the total costs are lower compared to truck transport [89].

For supplying a 66 MW power plant in Vienna (Austria), the fuel can be transported by road, rail and waterway (river Danube) first to a buffer storage facility where the material is chipped and then by truck to the conversion facility [90]. The modal split (truck–train) is preferable above 96 km in terms of energy requirements and above 250 km in terms of cost-effectiveness [90]. Given the case of a CHP plant (30 MW) in the urban district of Basel, transport by rail is cost competitive if distances are well beyond 100 km, whereas for short distances transshipment costs become too high [91]. Accordingly, the power plant “Alholmens Kraft” has a procurement area of within 200 km, trains can be used to bridge longer transport distances and the logging residues are collected within a 30 km radius from the train station [56]. Only 6 of 44 bioenergy conversion plants in Sweden that consume more than 100 GWh forest fuel per year have a direct rail connection; however, 20 have a railroad in the vicinity of the site. For this reason, a multimodal transport combination truck–train–truck is used for long distance transport [92].

In the past, hindrances to the rail transport of wood were inter alia state monopoly, high costs for inadequate service, lack of specialised wagons, inadequate rail network and lack of loading stations for wood including the close-down of some sections [89].

6.1.3. *Ship*

Ship transport has low variable costs and a low energy use per tonne kilometre [32]. However, time dependent costs are the highest compared with truck and train and, therefore, using ships is only economic over long distances [19]. Ship transport for forest fuels is possible on inland waterways (e.g. wood chips from Romania to Austria on the Danube [75]), or on the open sea (e.g. wood pellets form North America to the UK [16]).

Inland waterways are an important option for long distance biofuel imports. Some of the Eastern European countries along major waterways such as the Danube could export PFF competitively, but legal uncertainty and unreliable delivery service are hindrances at the moment [75]. However, there are still considerably unutilised capacities on many inland waterways such as the Danube [93]. Van Dam et al. [93] analysed options of biofuel trade from Eastern to Western Europe including railway, inland waterway and short sea shipping (e.g. from Poland to the Netherlands). The later one shows the most cost advantages for longer distances compared to inland waterway and railway.

Open sea vessels offer a great range of type and size, from less than one to several hundred thousand tonnes deadweight. Basically, a bigger size leads to more efficient transport, but the economically best size must consider inter alia port charges, tugging, velocity and cargo capacity [32].

6.2. *Terminals*

Basically, terminals balance the seasonal fluctuation of the plant’s demand and the respective variability of the supply from the forests. Therefore, terminals are used to ensuring a reliable supply even under extraordinary conditions as when wood piles in the forest cannot be accessed after a period of rain or heavy snowfall [75]. The storage of non-chipped and chipped forest fuels is an essential function of terminals, especially if storage capabilities at the plant location are low. Furthermore, the chipping process can take place at a terminal.

Focussing on a case study in Belgium, Van Belle et al. [94] analysed different storage options, from open air to roof covered and air fan. Costs were calculated using different storage durations, ranging from 0.32 Euro/m^3 for 3 month storage in the open air to 1.7 Euro/m^3 for a 12 month storage in a covered building with an air fan [94].

Seasonality of both, the fuel supply from the forest and fuel demand, leading to a maximum amount of forest fuels stored at a certain time of the year, determines the optimal storing capacity of a terminal [39].

Furthermore, terminals provide good services when the mode of transport is changed [95]. Terminals as large buffer storage areas are also prerequisites for ship and rail transport, as high volumes have to be unloaded and stored in a short time slot [75]. Transshipment creates additional fixed and variable costs. For North American road-rail conditions, the minimum shipping distance for rail transport was calculated to be 145 km for wood chip transport. Above this distance, lower rail costs per km offset the incremental transshipment costs [80]. Besides transshipment, a terminal can provide specific services such as weighing, measuring of moisture content, comminution or storing. Terminals differ in terms of the location, storage capacity, chipping technology and specific services provided.

Allocating a terminal with chipping operations has to take the vicinity of the settlements into account because of the noise and dust produced during chipping [96]. Thus, terminals distant to energy conversion plants provide a more acceptable place for chipping or crushing. Contrarily, in Austria a few terminals close to residential zones have been equipped with a sound-proofed hall, but next to additional investment costs, the handling of the forest fuel stored outside the hall increases chipping costs [75]. Usually, a chipper placed stationary at a plant is more cost-effective (economy of scale) than chipping at a roadside landing [21].

Setting up a terminal results in a trade-off between additional costs (e.g. investment and material handling) and decreasing chipping and transport costs due to scale effects [96]. Therefore, the cost cutting potential of a terminal depends on the entire PFF supply chain [97].

6.2.1. *Industrial terminal*

Industrial terminals are mainly located at a forest-based industry plant, where a stationary chipper is mainly used for chipping wood for pulp or panel production, but its capacity allows also handling forest fuels [75]. According to forest fuel supply chain cost analyses, terminals at energy conversion plants require a large storage area, a high annual volume to be processed, and a stationary chipper to be competitive [96]. Industrial terminals mainly use the existing infrastructure and profit from scale effects in acceptance of wood or chipping and thus provide low costs [21]. Accordingly, it was proved for the national forest fuel supply network of Austria that industrial terminals offer considerable saving potentials [97]. Consequently, a forest-based industry partner as a terminal provider can offer important cost cuttings. Furthermore, an industrial terminal using a stationary chipper can be located directly at an energy conversion plant. Some industrial terminals are not located at sites of the forest based industry, for example the terminal of the bioenergy conversion plant in Vienna (Austria). There, the fuel can be transported by road, rail and waterway (the Danube) first to a buffer storage facility (where the material is chipped) and then by truck over approx. 6 km to the conversion facility [90].

6.2.2. *Train terminal*

Train terminals have been established within the last decade mainly in Northern Europe, partly induced by huge amounts of wood that had to be stored and further transported by train after dramatic storm damage. These terminals were built as transshipment points for multimodal long distance transport, since sources (i.e. dense woodlands) are distant from large bioenergy conversion plants. Transport 1, as defined above, is always done with trucks (due to the accessibility of forest roads), while for transport 2 trains are the economical alternative for longer transport distances. Some critical success factors have been identified, for example the number of trains despatched per week, due to high fixed costs, and utilising the maximum payloads for each train or wagon, hence precise weighing is needed. In addition, fast and efficient loading is necessary and, therefore, the distances between chip piles and train wagons should be kept short. Additionally, a long planning horizon for rail transport must be considered. Big terminals, used for both, roundwood and PFF, are more efficient than smaller terminals. On the other hand, a disadvantage of such combined terminals is sometimes a longer distance between rail and chip storage, since the logistics is usually optimised for roundwood [[92,98–100,101], all in Swedish].

6.2.3. *Simple terminal*

Simple terminals (also named regional terminals, processing areas or satellite sites) in or near the forest provide only storage area for several thousand cubic metres of wood, as well as year-round access for trucks and mobile chippers. Often entrepreneurs with mobile chippers are engaged, since the volumes chipped are low. Compared to the annual demand of a CHP, the storage capacity of a regional terminal is relatively low, and the same applies to scale effects on chipping and transportation [97]. In addition, agricultural infrastructure such as terminals built for processing sugar beets, providing a calibrated weighbridge and asphalted storage surface, are used as forest fuels terminals [75]. Further examples of simple terminals are documented for the US [81], Scotland [102] and New Zealand [18].

7. Supply chain management

7.1. *Supply chain costs*

In order to analyse PFF transport systems in New Zealand a simulation model was developed to compare different supply systems. Seven systems with road transport were applied on three different forest sites (the total transport distance to the final destination from site I is 25 km, from site II 50 km, from site III 75 km). The transported assortments were loose residues and chips. Several storage options and changes in moisture content and dry matter were included [18]. Cheapest of all the sites was the direct truck transport of loose residues from the forest landing to the bioenergy conversion plant where the material is chipped [18].

Focussing on a case study in Belgium, Van Belle et al. [94] analysed supply chains for PFF including wood resources, potential suppliers and financial, economic and environmental constraints. The two analysed transport systems are both using trucks, one with two containers of 35 m^3 each and the second with a semi-trailer with a 70 m^3 bin. The latter has higher annual transport quantities and lower costs per kilometre (0.2 Euro/odt/km return for softwood) [94].

Looking at the development of the last three decades, the concept of the experience curve can be also observed in the PFF supply. Accordingly, analyses of the Swedish and Finnish forest fuel supply chain show that the main cost reductions were achieved in forwarding and chipping, owing to learning-by-doing, improved machinery and changes in organisation. Contrarily, net transportation costs remained rather stable within the last three decades. According to the data of these two Nordic countries, the resulting experience curve shows a progress ratio of 85% at a correlation coefficient of 0.97 [103].

Ranta and Korpinen [104] evaluated the maximum availability of PFF within a region in Finland by means of GIS (Geographical Information System). Theoretically, the procurement areas are represented by perfect circles. If the available biomass is uniformly distributed and the network infinitely dense and perfectly straight, the average transport distance is 2/3 of the procurement area radius. Increasing the procurement area by a factor would increase the transport distance by the square root of that factor. However, even more than agricultural biomass, forest biomass is scattered in numerous small felling sites in spacious territories and the accessibility through transport networks is limited. The same authors stated that topographies, road networks, land-use and varying potential of PFF per area (MWh/km^2) must be used for realistic models. Therefore, they calculated a winding coefficient for each plant site and different distance classes (40, 60, 80, 100 km); the winding coefficients varied between 1.26 and 1.42.

Mahmudi and Flynn [80] developed cost curves for road and rail transport, calculated the "*minimum economic rail shipping distance*" and analysed the optimum number of transshipment terminals that minimises overall transshipment costs. In a road-rail-system minimum shipping distance for rail transport for wood chips was estimated to be 145 km. Above this distance travelled by rail lower costs per km offset the incremental transshipment costs [80].

Costs for supply chain management can be reduced by employing an Internet-based, general-purpose logistic control system, using mobile data terminals in forest fuel chipping and transportation [86]. Accordingly, the amount of cost-savings for forest owner associations in Finland, if electronic supply chain management applications are implemented for truck logistics, was evaluated by cost-benefit analyses using the net present value methodology. The results show that supply chain management applications increase the profitability of energy wood procurement through improving work flows and thus reduce the work input [105].

The costs of potential road transportation systems for PFF were analysed for Canada. For short transport distances, the total costs per unit transported and comminuted mainly depended on the cost efficiency of comminution, but for longer distances the truckload capacity and relocation costs are more important. On the other hand, the transport of uncomminuted forest residues is competitive only when landings are very small and transport distances are very short. For greater distances, the chip system is the most cost-effective, but if transportation distances are high and the cutting blocks small, the bundling system becomes competitive [59].

Under Scottish conditions, competitive PFF systems mainly rely on chipping wood at the roadside and truck transport. Chipping at the plant would be cheaper, but is often impossible since many plants are located in urban areas. With long transportation distances (>100 km) terminal chipping is cheaper than roadside chipping [102].

The assessment of the delivery costs of agricultural and forest biomass (including loose forest residues, wood chips and bundles as well as pellets produced of residues and sawdust, respectively) proved that delivery costs for a single biomass type is higher than for a combination. Furthermore, a combination of different biofuels is economically advisable for big bioenergy conversion plants [29].

Based on Finnish conditions, simple supply chains (e.g. truck transport of loose residues and chipping at the plant) are most competitive, whereas for long distances, supply chains providing a higher packing density and using full loading capacity become more important [89].

Japanese forest are characterised by much steeper topography compared with Nordic forests, which hampers the use of in terrain processing of forest residues [73,74]. Whole tree yarding/skidding concentrates residues at a forest landing [106]. Under Japanese conditions it was proved that the earlier comminution is incorporated into the system, the lower procurement costs are [73,74].

7.2. Decision-support systems, optimisation and simulation

Both simulation and optimisation models can be used to gain insight into the logistics of biomass supply chains [107]. A simulation model divides the biomass into lots, which run through the network. The results (e.g. costs) are calculated per lot. A simulation model adopts a preset network structure and enables comparisons between different structures. Simulation is a capable method for analysing problems like queueing, where different solutions are compared instead of determine the optimum. In contrast, an optimisation model calculates the optimal network structure or the optimal mixture of resources. A simulation model can consider changes in dry-mass and moisture content depending on time. An optimisation in contrast gives only the flows per time period. Simulation shows the time course of flows, while optimisation can hardly include time-dependent effects [107]. However, De Mol et al. [107] state that by adaptations and approximation some of these differences can disappear – but not all.

The problem of locating the point(s) of comminution, terminal(s) and/or energy conversion plants addressed in the most of the following studies is related to the well-known warehouse or plant location problem [97]. Several authors [cp. [108,109]] provide a comprehensive survey of model formulations, solution approaches, and applications ranging across numerous industries. Resource allocation is a critical task for forest fuel supply, since non-optimal allocations result in higher transportation distances resp. costs [110].

Rönnquist [111] provides a broad and general overview of optimisation models actually used in forestry, including forest management and harvesting, transportation and routing as well as production planning for decisions on strategic, tactical and operational level. In addition, Troncoso and Garrido [112] illustrate strategic decision problems for forestry production and logistic planning where dynamic mixed-integer programming is often used for solving plant location problems. The use of geographical information systems (GIS) support analyses of spatial relationships between the locations of forests, plants and transport infrastructure. GIS for biomass supply chains provides spatial statistics, network modelling, geographical overlay and visualisation [40]. Additionally, forest industry examples of applications of supply chain management and optimisation are provided by Carlson and Rönnquist [113].

7.3. Models

That optimising PFF production necessarily means minimising transportation costs, was already shown in early studies [114]. An LP model was successfully applied on an energy wood supply system in Sweden [114]. In the analysed case, it would be favourable to use more logging residues and sawmill by-products and less wood chips resp. tree sections. Changes in transport and comminution are also suggested: The use of mobile chippers on different sites and the direct supply of heating plants should increase; the transport of forest residues to a terminal with a stationary chipper and further transport of chips should decrease [114].

Jourquin and Beuthe [115] developed a simulation model to describe multi-modal freight transport with the GIS-based software tool NODUS and apply the model to the trans-European freight network of roads, railways and inland waterways for the transport of wood. After creating an origin-destination matrix and the cost functions for transport operations it was possible to minimise the total transport costs by selecting the optimal combination of routes, modes and means and therewith determine the modal split and analyse the competitive position of these three inland modes of transport [115]. Increasing the costs of road transport through taxation shifts transport quantities to the other modes and railway transportation is much more sensitive to a cost variation of road transportation than inland waterway transport; that may be because of the network structure.

An activity oriented stochastic computer simulation model was applied to mapping the biomass flow from felling in the forest to storage at the industry. Reducing the inventory times in the forest, at the roadside and at the mill yard showed tremendously reduced costs. The expense of inventory time was due to value losses (fibre deterioration) and interest rate [116].

For co-firing forest fuel in coal power plants, the total purchase and transportation costs were estimated by a GIS-based model that proved the importance of a plant-based approach for assessing biomass resources and procurement costs [117].

For Irish peat power plants that were retrofitted to enable the firing of wood chips from short-rotation willow plantations economic analyses were carried out evaluating the main transport parameters for willows (chips in containers, bundles, loose sticks) as well as storage options [118].

Cundiff et al. [119] built a linear programming model as a planning tool for the supply chain of switchgrass for the ethanol production with the overall objective to minimise costs. Stochastic uncertainty due to weather-related factors was addressed by formulating a two-stage linear programming with resources. Another stochastic model can be found by Rauch [30] who used stochastic simulation for evaluating the impacts of supply chain risks on forest fuel procurement costs.

Asikainen [76] developed a discrete-event-based manufacturing simulator of a chipping terminal. The constructed simulation model starts at the terminal where energy wood is stored. Comminution was modelled either as chipping directly onto a truck or chipping onto the ground and loading by wheel loaders. Transport can be carried out by three different kinds of trucks (truck with a draw-bar trailer, truck with a semitrailer, truck with interchangeable containers). Waiting and queueing at the terminal increased the costs. For all distances, it was efficient to use a separate loader and two trucks and to chip independently [76]. Furthermore, discrete-event simulation was used to model and to analyse truck arrival and unloading processes at a Finnish bioenergy conversion plant in order to minimise truck queueing times and to balance the use of two delivery platforms [120]. The most practical way for reducing queueing times is to direct the trucks to the delivery platforms with the shortest queue. Furthermore, scheduling the trucks arrivals was useful too [120].

The concept of dynamic programming for feedstock supply chains was described by Gigler et al. [121] and illustrated with a case study on willow biomass. In contrast to other products PFF can substantially change the moisture content during transport and storage. While De Mol et al. [107] considered simple relations for dry mass loss and moisture content, Gigler et al. [121] incorporated differential equations to describe quality development.

A GIS-based method for the least cost allocation of forest wood chip resources to energy plants within Denmark used a cost-weighted distance to wood chip resources and the annual demand as decision parameters. The model allocated each supply of wood chips to plants along the least-cost paths in terms of travel time, until the demand of each plant is met or the chip source is exhausted. Resource areas are mapped on a national scale and the cumulative and total costs of supply for each plant are calculated [40].

In order to support supply chain planning for heating plants firing both forest and sawmill residues, Gunnarsson et al. [95] developed a Mixed Integer Linear Programming (MILP) model. Decision variables were fuel assortment (e.g. forest residues, sawmill by-products, or decay-damaged wood), transportation modes, and harvest areas resp. sawmills. The model supports decisions (i) on where and when forest residues should be comminuted, (ii) how to transport and store forest fuels in order to satisfy demand at bioenergy conversion plants and (iii) if additional harvest areas or sawmills should be contracted in order to purchase forest residues or sawmill by-products.

Sustainable biomass availability as well as harvesting and transport costs are crucial parameters for allocating energy conversion plants and calculating optimal capacity. Accordingly, Freppaz et al. [122] optimally allocated six plants and designed the supply network applying a MILP model. The sites of the bioenergy conversion plants where decided previously due to political reasons, while optimal size, optimal share of heat and power production, and optimal exploitation of biofuels were calculated afterwards by the model.

Hamelinck et al. [32] illustrated several international biomass supply chains, including various forest residues as well as other sources originating in Europe and South America. Treatments such as comminution and densification are included in the study as well as storage and the resulting mass losses, which can reach up to 15% of solid biomass. Costs of different transport chains (including truck, train, ship and multimodal transport) are compared. For the transport within Europe, the total costs arise from high production costs and relatively high road transport costs [32]. The first transport in the chain, from forest to simple terminal, has no return freight and due to large spatial distribution, the distances are quite long or the applicable scale remains small. In contrast to expensive train transport, international ship transport has only a moderate part of the total costs [32]. Overall supply chain costs do not decrease at larger scales, since the supplied fuel is more expensive and truck transport efficiency does not improve [32].

Multi-scale spatially explicit analyses of the PFF supply and demand that illustrate the local heterogeneity at the regional and national levels were implemented by a GIS-model called WISDOM [123]. First, the demand module illustrates the spatial distribution of PFF consumption. Second, the supply module displays a spatial representation of all PFF sources including current stock, changes over time and productive capacities. Then, the integration module analyses relevant interactions between supply and demand. The model allows for an evaluation of the sustainability of PFF use in a certain region and supports strategic planning and policy formulation [123]. A case study performed for an Austrian province proved that a supply chain using an industrial terminal outperformed all regional terminals that were located within a radius of 100 km.

Polagye et al. [124] describe the situation in the western US, where overstocked forest areas, huge in size and far away from end-use markets, should be thinned to prevent forest fires. The energy use includes co-firing wood chips in coal power plants, steam cycle cogeneration, and production of three bio-fuels: pellets, bio-oil (via fast pyrolysis), and methanol (via gasification and gas-to-liquid synthesis); additionally non-energy options, sale as pulpwood and disposal, were considered. The conversion into these products can be carried out in stationary plants outside the forest or mobile units at the logging decks. If bio-fuel is produced at the logging deck, the transport costs will be minimised, but production costs would be much higher compared with a large, centralised facility. Bio-fuel production using mobile or transportable facilities is significantly more expensive than production at a stationary facility. For a 100-km-distance, the sale of pulpwood is economically preferable, because this is the least capitally intensive option. Co-fire of wood chips is competitive for all except the lowest available quanta of PFF and for transport distances up to 400 km.

Panichelli and Gnansounou [125] used a GIS-based decision support system for allocating bioenergy conversion plants solving the resource competition problem between facilities using a location-allocation model based on least cost supply.

Perpiná et al. [126] developed and applied a methodology to optimise the use of agricultural and forest residue biomass by means of GIS. It describes the spatial allocation of biomass for energy use and the ideal sites for bioenergy conversion plants on a regional scale. In contrast to Freppaz et al. [122], who used previously defined sites for bioenergy conversion plants, Perpiná et al. [126] implement a model which selects the most suitable locations out of all possible locations.

In order to combine GIS spatial studies with linear programming models, a network from a digital map has to be designed by an algorithm selecting points on the map for the locations of a bioenergy conversion plant and minimising logistic costs to supply consumers [127]. In addition to a theoretical description, a practical example is shown for a region in Spain, where available biomass consists mainly of wood residues coming from the pruning of olive trees and vineyards [127].

Bauen et al. [128] include in their broad study on supply and demand of bioenergy from short rotation forests in the UK inter alia calculations for logistical costs and the optimal site location and use LP models. Yield maps for miscanthus, willow and poplar, constrained by climatic, soil and land use factors, are used to estimate the potential resource. Resource distribution and associated production costs are the basis for energy crop supply-cost curves. The results show a considerable potential for energy crops in the UK, offering a competitive source of renewable energy [128].

A more recently developed operational forest fuel logistics model implemented daily variations in the moisture content of the delivered wood chips as well as weather conditions that slow logging operations. The model estimated feedstock supply for a potential 300 MW power plant in British Columbia using salvage wood due to severe mountain pine beetle infestations [43]. For a woody biomass-based conversion plant, a model supporting the choice of energy conversion technology (grate-firing combustion, fluid-bed combustion, fluid-bed gasification, and fast pyrolysis) was set up including the biomass procurement costs [129].

Rentizelas et al. [130] developed a decision support system that aims to support investment decisions (e.g. plant allocation, plant size, procurement area, feedstock assortment). The demand-driven model covers a multi-biomass supply chain for a plant producing three types of energy (electricity, heating, cooling) and includes the whole bioenergy system. The consideration of the trade-offs of different storage methods is important, which have different economic parameters, i.e. investment-, logistic- and storage costs, and different influence on product quality, i.e. dry matter loss [130].

Eksioglu et al. [131], designed a supply chain for producing ethanol from agricultural and forestry biomass. They formulated a multi-period mixed integer programming model (MIP) that minimises the total procurement costs and integrates long-term supply chain design and mid-term logistics management. A further application to a forest fuel supply MILP was to test the robustness of the network design by means of a parametric sensitivity analyses. Moreover, robust terminal sites were estimated by testing competitiveness under different transportation costs and domestic forest timber utilisation rate scenarios. Transport cost increase showed that the optimal network design was stable within a wide range. Furthermore, the number of terminals decreased when domestic forest timber utilisation rate was increased [97].

Schmidt et al. [132] used a mixed linear integer programming model to find advisable locations within Austria for installing biomass-fired CHP plants. The model considered the production and transport of biomass, the conversion into heat and power and district heating system. Plants were located in densely populated regions (bigger cities in the east of Austria) due to heat demand.

Rauch [30] modelled the influence of stochastic risks on forest fuel supply by means of a Monte Carlo simulation and evaluated the economic performance of two fuel-sourcing models supplying a single CHP plant. Results proved that a forest fuel supply chain storing salvage pulpwood as feedstock had 1–3% lower procurement costs than a supply chain without storing salvaged pulpwood and that storage of salvage pulpwood considerably reduced supply chain risks.

Alfonso et al. [41] present an optimisation methodology using GIS to assess optimal management and energy use of scattered and divers biomass resources and apply it to the Valencian region in Spain. Logistics is a main factor but other features are also considered: biomass resources properties (quantity, quality, seasonality and availability), plant size, bioenergy technologies, CO_2 emissions and demand.

A MILP model on the forest fuel supply network on a national scale for Austria was designed by Rauch and Gronalt [75]. The model includes decisions on transport modes (road, rail and ship), number of terminals and their spatial arrangement. Scenarios are formulated to study the impact of rising energy costs and route optimisation. Railway has a minor share in all scenarios because the initial transport is always done by trucks and the total transport distances are relatively short within Austria. The Danube as an inland waterway is considerably important in this model as the transport mode for long distance imports.

Costs, net energy benefits and CO_2 benefits of various systems for using logging residues locally, nationally or internationally are studied by Gustavsson et al. [133]. Several different transport modes and distances are studied including truck, train and ship as well as terminal systems and multi-modal transport. Primary energy requirement for recovering, refining and transporting PFF is minor compared with the fuels' energy content and the costs of long-distance transport were lower for wood pellets, but total costs were less for bundle systems.

Rauch and Gronalt [75] presented an MILP model optimising the forest fuel supply network for Austria. The supply network included national and international supply regions, the transportation modes of road, domestic waterway and rail on a national and international level as well as different terminal types. Furthermore, the impacts of rising energy costs on procurement sources, transport mix and procurement costs were evaluated. Their results show a 20% increase of energy costs resulting in a procurement cost increase of 7%, and an increasing share of domestic waterway transportation.

7.4. *Critical aspects of MILP, LP*

MILP models usually minimise specific costs under the assumption of perfect co-operation and coordination among all involved business entities. Contrary, due to competition, the calculated costs are certainly lower than in reality as was proved by Rauch et al. [134] who found that real costs were at least 20% higher. For simulating a competitive situation they applied three different heuristics figuring out the practical behaviour of managers supplying a single CHP.

Further frequent shortcomings of network models are the exclusion of long-distance transport modes of rail and ship, assumption of too small procurement areas, neglecting supply and demand of adjacent regions resp. competing material uses (e.g. panel production) and disregarding import options. Moreover, even though several models support strategic decisions with a long term planning horizon, basic economic assumptions are market stability in terms of supply volumes and prices resp. supply costs.

To some extent, the planning horizons of the models are inappropriate to the decisions that should be supported. Strategic decisions usually have a planning horizon of about ten years and have to consider the actual and future trends and possible effects on business environment, whereas some models supporting strategic decisions (e.g. forest fuel network design) only consider one year or if considering several years, the parameter setting is in most cases stable.

Additionally, most of the presented models are not sensitive to stochastic supply delays caused by natural hazards or technical breakdowns. However, the resulting delays of terminals or direct supplies have a considerable impact on economic performance of the supply chain and should be considered in the supply network design, (e.g. if additional terminals are needed for fuel buffer stocks, cp. [97]).

Similar to other supply decision models many of the presented approaches focus on a single parameter (e.g. mainly forest fuel procurement costs) and are in danger of producing sub-optimal solutions to the sourcing problem [135], because multiple criteria (e.g. supply security, product quality, risk splitting) are important in sourcing decisions. Furthermore, model results can strongly rely on specific parameter assumptions (settings), for example Lindroos et al. [59] note the strong dependence of the results on payload assumptions. Unfortunately, critical comments on the own model as well as documenting found shortcomings by the authors themselves is rather rare.

Roos and Rakos [136] discussed the limits of modelling the bioenergy sector. Modelled energy systems often differ from "real life" energy systems because they disregard some of the following reasons: political influence, behavioural aspects of private consumers (e.g. environmental concerns), information asymmetry, learning curves for both individual plants (bioenergy conversion plants have often a trials-and-error phase when starting operation) and whole industries, allocation of costs between main products and bioenergy products (e.g. roundwood and forest residues), dependence on local conditions and many biofuels are due to low energy density not globally traded. However, Roos and Rakos [136] state that a model built between comprehensiveness and complexity cannot include all the factors potentially influencing the outcome.

8. Outlook

When reviewing papers dealing with PFF supply chain research, one faces a variety of similar terms dealing with costs (e.g. system costs, procurement costs, supply costs, transport costs). A precise definition on what is meant by a specific term is absent in many publications. Moreover, homonymous costs are not necessarily calculated similarly. Hence, we see a need for future work to clearly define and use terms within the scientific community and the praxis.

Most of the research on the transport of PFF deals with road transport (mainly as single echelon unimodal transport), less research was carried out on train transport, while waterway transport is scarcely documented. However, multimodal transport (sometimes referred to as combined transport) has been studied to some extent. No scientific publication could be identified where PFF is transported on an intermodal transport chain. A reason could be found in the fact that PFF is a bulk product with low energy density and low price and transport is relatively expensive compared with the material's value. Therefore, transport distances are usually rather short. However, international transport of comminuted or compacted PFF grow in interest and, in addition to multimodal transport, intermodal transport would be an option that needs closer examination.

Moreover, if bulk density and energy density of forest fuels are increased by further processing, resulting in secondary forest fuels (e.g. torrefied pellets), longer transport distances seem economically feasible and intermodal transport is more likely. Additionally, intermodal freight transport research is a growing field [24] and applications within the biofuel sector could be addressed by future research. Beyond that, research on intermodal biofuel transport will also result in developing specific loading units (e.g. containers) that fit to an intermodal transport chain.

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