Chapter 6
Biomass Harvesting and Logistics

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6.1 Introduction

As with conventional timber harvesting and transport, the selection of machine systems for biomass production is often based on local availability, traditional harvesting methods and systems and the innovative spirit of entrepreneurs. However, piecing together an optimal biomass harvesting and transport systems to fulfil sustainable biomass supply requires substantial knowledge and insight into and of the whole biomass supply chain. When considering the number of potential options available at any decision point in the chain, it becomes apparent that biomass supply chains are in fact unidirectional supply networks and not single or unique chains. The best employment of production factors represents the minimum cost flow through the network, from standing tree to boiler grate. Knowledge of the options available and the consequence of employing each of these is therefore important in plotting the best way forward through the network.

Biomass production networks are characterized by a number of state and form combinations. The required state or form of the biomass, e.g., Full-tree (FT – felled trees with branches and top intact), Tree-length (TL – trees felled, debranched and top removed), Cut-to-length (CTL – log assortments), and comminuted material,

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at each stage in the network (e.g., at stump, roadside landing, terminal, plant) determines, or is determined by, the production methods. Some of these can be directly linked in function and time, while others can be totally detached. A full year may pass between extraction and processing of stumps while in some cases hardwood trees can be felled, chipped and combusted on the same day.

Almost all final consumption plants, whether for combustion or as a raw material in further processing to; e.g., briquettes or pellets, requires biomass in a chipped or crushed form. This process of conversion is called comminution. A challenge for the operations manager is determining at what stage in the network comminution should happen. Every alternative has consequences for the choice of harvesting, extracting, processing and transport equipment. In the following overview, examples of a supply network in which comminution takes place at each cardinal point; in-field, at roadside, at a terminal, and at a conversion plant are provided. This chapter provides the reader with broad insight into making these comminution decisions through discussion of the positive and negative aspects at each of these cardinal points.

The proliferation of publications, trade fairs, seminars and internet sites (e.g., www.forestenergy.org) providing information on biomass production equipment and machinery, and the rapid technical developments that are being undertaken limit the relevance of a detailed technical description. In the following section, the working principles and intentions behind the main categories of equipment and machinery are presented and the reader is urged to keep abreast of developments through other media.

6.2 Biomass Felling and Extraction Harvesting Equipment

Felling is a prerequisite of any wood based biomass supply, whether it takes place as an integrated part of traditional roundwood harvesting or as a specific biomass harvest. In this section, distinction is made on the most important types of felling technology. Felling methods range from motor-manual (chainsaws and brush-cutters) to fully mechanized systems, each with rational areas of application. Although mechanised harvesting systems have been practiced for at least three decades, motor-manual methods have been a traditional and historic part of biomass and timber procurement since the early 1950s.

The use of chainsaws and brush-cutters are at times (depending on technological level of the organisation involved with bioenergy production, terrain, extraction system and biomass type and dimension) the preferred means of changing the state of the standing biomass. The felling of spiny or thorny biomass places limitations on the use of motor-manual felling systems, as it is difficult to approach the biomass. Multi-stemmed biomass also negatively impacts motor-manual productivity, particularly when individual stems are of small diameter. Typically this situation requires the use of mechanised multi-stem felling systems to overcome piece size challenges.

In developing countries the use of chainsaws in conventional FT, TL and CTL operations from which biomass residues are retrieved remains an integral part of the harvesting supply chain; i.e., felling, debranching, cross-cutting and topping, where applicable. However, productivity, worker safety and biomass product quality are marginal and modern mechanised systems for felling, debranching and cross-cutting are becoming more the rule than the exception (Pulkki 1992, 2000).

Mechanised felling (and extraction) systems are based on agricultural tractor units, excavators, or purpose-built forest machines, such as feller-bunchers, harvesters or forwarders. What distinguishes these machines from each other is their stability in the terrain, operator safety (ROPS, FOPS and OPS) and working capacity at the boom tip. But caution should be exercised when applying agricultural tractor/trailer systems in forwarding of biomass due to these units operating outside their intended design specifications.

In mechanised systems the felling, handling and eventual processing of the biomass is done using one of a number of specialized harvesting and/or processing heads categorized below. It is generally not necessary to use a sophisticated head for biomass harvesting as specifications on dimensions or quality are low or non-existent. However, some type of multi-stem capability is preferable. Mechanised felling equipment can be categorised as follows:

- Felling head: a felling head grasps a tree and fells it using one of a number of cutting technologies (i.e., chain saw, disc saw, shear, auger) (Fig. 6.1). The felling head is lighter and cheaper than other heads but cannot process a tree, i.e., usually is not fitted with feed rollers or debranching knives.
- Harvesting head: this head has the ability to grasp a tree, fell it, lower it in a controlled fashion/direction, and process it (i.e., debranch, measure the length and cross-cut).
- Accumulating head: this can be either a harvesting head or a felling head that has been fitted with accumulating arms which can hold multiple stems on a plate on which to rest the butt ends.
- Processing head: this head is typically fitted to an excavator or loader boom and is used for processing (i.e., debranching, cross-cutting, and in some cases debarking) FT that have been felled and gathered (e.g., at a landing). These heads do not have the capability to fell trees.

The size and type of the base machine, the crane type, forest conditions and operator skill all influence productivity. A larger base machine would be more stable and powerful when working a bigger head, or accumulating more trees, at a greater distance from the striproad (boom reach). However, smaller scale systems (e.g., agricultural tractor with crane and lightweight felling head) do and will continue to fill an important role in biomass procurement (Russell and Mortimer 2005).

Fig. 6.1 Felling head using a disc saw with a high tolerance of dirt, stones or carbonized bark (Photo: Talbot)

6.3 Collection and Extraction Equipment and Machinery

The extraction of loose material that is not chipped and which weighs less per load than solid wood is less damaging to the site than infield chipping and extraction of heavier loads on the same site (Stupak et al. 2008). This is due to the lower mass and bulk density of the material and reduced impact of the total mass on the soil surface. It also results in inefficiency; however, as less tonnage is extracted due to the loads being volume-restricted. Residual biomass harvesting system selection decisions therefore need to match biomass type with specific machines to result in optimally productive and cost efficient harvesting systems (Stupak et al. 2008). Conventional harvesting systems, which are presently in use form the basis of residual biomass harvesting systems selection, and are dependent on the location of comminution:

- Terrain chipping
- Chipping at roadside or landing
- Terminal chipping
- Chipping at processing plant

However, conventional forwarders or agricultural tractor/trailer units fitted with forestry trailers (i.e., with crane and bogie axle), encompassing CTL, TL and FT systems remain the preferred means of extracting small trees, bundles, tree parts or harvesting residues. This is due to their design and availability to the sector.

These come in various adaptations, all of which aim to maximize the payload of a bulky, low mass product and selection remains specific to particular situations. A FT system incorporating cable and/or grapple skidders is an option as an integrated roundwood/biomass harvesting system provided sufficient space is available on the landing to cater for storage of the resultant biomass. From this point decisions can be made to either comminute at roadside or transport the loose biomass further towards the final consumption point.

6.4 Chipping Equipment and Machinery

Chipping is the most common method of comminuting biomass in preparation for combustion or other form of energy conversion. The two predominant chipping types are disc chippers and drum chippers (Fig. 6.2).

The working principle of the disc chipper is that 2–4 bevelled knives are fixed radially in a fast rotating disc. The knives, which can be adjusted for desired chip size (measured in the fibre direction) cut the biomass perpendicular or slightly offset to the feeding direction, and run up against an anvil to ensure the material is severed. A fan blade mounted on the rear of the disc creates a pneumatic force that blows the chips out of the spout and into a container or onto the ground. In larger chippers (>40 cm intake), the disc can have a diameter of over 120 cm and weigh more than 1,000 kg. Because the disc always cuts at a constant angle to the material, the disc chipper can produce very uniform chips. Disc chippers produce more 'stickers' than others (long slivers which cause stoppages in conveyor systems) as these are pulled into a parallel orientation to the knives. Various solutions have been found to reduce that problem which is more pronounced in small material (small trees, tops and branches).

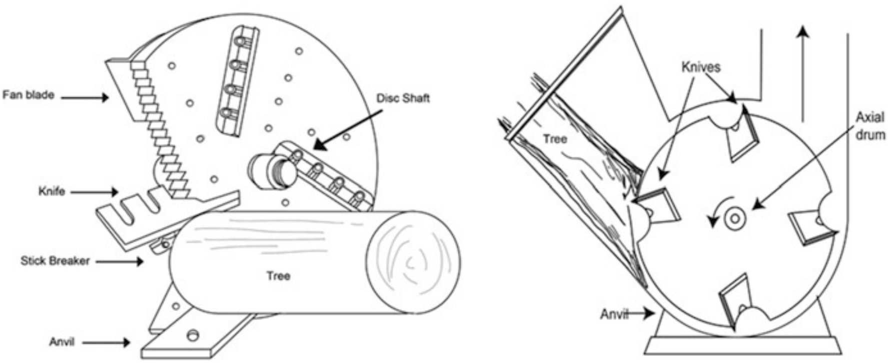

Fig. 6.2 Illustration of the working principles behind the disc and drum chipper (Danish Centre for Biomass Technology)

The drum chipper consists of a number of knives mounted along the longitudinal axis of a steel cylinder, with a smaller diameter than the disc chipper. It is therefore more compact and can be built into smaller spaces (e.g., on chipper trucks). By nature of its design, the knives on a drum chipper cut into the material at different angles, depending on the size of the log or branches. This produces slightly more heterogeneous chips. The drum chipper can generally be built for larger diameter logs, or larger bunches of smaller material, as the disc chipper intake has to be limited to less than the radius of the disc. Provided enough power can be delivered to the drum, it is possible to build drum chippers with larger intake capacities. The length of the knives reduces the negative consequences of hitting dirt or a stone as this would represent a smaller proportion of the knife than the same damage on a shorter disc knife. The knives on both disc and drum chippers have to be maintained (sharpened or reversed) at least once a day, and even more frequently when working with material that has been contaminated with soil, sand or stones, or cutting carbonized bark.

Auger or conical screw chippers are robust and produce homogenous chips of good quality. However, they require much higher power drivers, due to the high forces required in severing the material that is fed in the same direction as the axis of rotation. Chip size is adjusted by exchanging the screw for one with a different pitch, while the whole screw needs to be sharpened in place, or exchanged for a newly sharpened one. An advantage of screw chippers is that large material (chunks – up to 150 mm) can be made for e.g., thermal-gasification. Irrespective of the working principle, chippers are deployed in many sizes and configurations. Some are built onto terrain going base machines, others on trucks or trailers for mobility, while others are located centrally at terminals or conversion plants.

6.5 Biomass Sources and Harvesting Systems

This section discusses the utilization of the most economically accessible biomass resources arising from plantation forestry that include:

- Early thinnings, or dedicated energy roundwood.
- Harvesting residues (i.e., branches, tops and off-cuts).
- FT or salvaging from calamities (i.e., insects, wind, forest fires).
- Stumps and other sources.

Probably the most fundamental issue of biomass supply systems is that they consist of a number of stage-state steps between the standing tree and the boiler grate. Each step requires an action or selection of a method or machine that has implications for the whole downstream chain, and which cannot be reversed. The choice of felling method reduces options for processing or extraction. A decision to do in-field chipping eliminates the option of conventional forwarding and transport. There are a larger number of stage-state combinations, alternating between change of location and change of form, and only the most predominant are discussed in this section.

6.5.1 Harvesting Biomass from Early Thinnings

Unlike forests managed under more natural conditions (e.g., natural forests and woodlands selective cutting and the retention of seed trees for regeneration), plantation forests are typically re-established through the planting of seedlings. The important connotations of this are that spacing is controlled and that trees are typically planted in a geometric pattern which promotes efficient harvesting.

Early thinning is a term often used in conjunction with pre-commercial or sub-economic thinning and this well justified term is continually verified in research. It refers to an operation in which re-spacing is required to be carried out for the benefit of stand development, but the economic results of doing so do not necessarily justify the operations in themselves. Ahtikoski et al. (2008) use a complex calculation showing that energy wood thinnings could be financially viable if the extracted volume at least 42 m^3 ha^{-1} for an average stem volume larger than 0.015 m^3 and the unit price delivered exceeded US$12.00 MW h^{-1}. Plantation managers can partly avoid this cost by expanding initial planting espacement and accepting the consequences of later canopy closure, but the debilitating relationship between productivity and tree size cannot be totally avoided.

However, in cases where a market for smaller roundwood has fallen away (e.g., loss of contract or closure of plant) the demand for biomass could promote early thinnings. Also, the development of a bioenergy conversion facility should stimulate denser establishment (higher number of stems per unit area) on areas that have been managed more extensively (refer Chap. 5). To promote efficiency through mechanized operations, variable row spacing can be used (e.g., closer spaced double rows which will be removed in the first thinning and more widely spaced rows that will not be thinned).

Small trees can be felled in a number of ways, largely determined by the extraction system to be used. Motor-manual felling with a chainsaw is often the most cost effective way of felling trees when they do not need to be processed in whole-tree harvesting (i.e., tree parts and crown intact). This is especially true if the trees will be chipped as they lie in the stand or if they will be extracted with a cable system (e.g., high lead or monocable). If pre-bunching or processing is required, then mechanized felling is preferable. However, opening up of strip roads can be costly if the bunches have to be laid perpendicularly into the stand, as placing them in parallel requires wider striproads, and if driven on they can be contaminated with mineral soil and stones, resulting in increased ash content of the eventual product.

An agricultural tractor fitted with a boom and a multi-tree (or accumulating) felling head can provide a low investment alternative to a feller-buncher or harvester, but versatility is dependent on terrain conditions (Russell and Mortimer 2005). In a study in Scandinavian forests, productivity levels of 3–6 m^3 h^{-1} were obtained for felling and loading small trees onto a trailer for extraction (Belbo 2010). Small tree size thinning harvesters fitted with accumulating felling or harvesting heads are popular because of their greater stability and terrain going capability. However, all harvesting systems are highly sensitive to tree volume (Fig. 6.3).

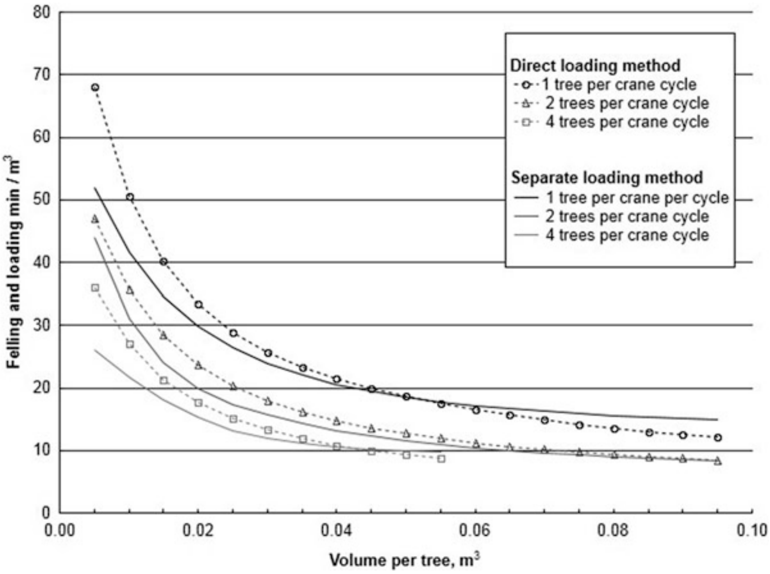

Fig. 6.3 Influence of direct loading and the number of trees per crane cycle on the combined felling and loading time using a Nisula 280 felling head in small trees, by increasing tree size (Belbo 2010)

The extraction of small FT or energy roundwood to roadside can be done using forestry equipped agricultural tractor/trailer units, a grapple skidder or a forwarder (Fig. 6.4). FT have a low bulk density and the load can potentially be compacted with the crane and grab. If the trees are to be extracted individually (e.g., using a monocable or a chute) or if they are to be chipped with a terrain going chipper machine they can simply be left as they fall for transpiration drying and subsequent extraction.

6.5.2 In-Field Chipping of Full Trees/Tops

When FT are harvested in a structured manner, and terrain is easily accessible, it is possible to use terrain-going chippers. These are commonly built on a standard forwarder chassis or adapted agricultural tractor fitted with a crane to feed the chipper and a large bin or skip to hold the chips. The orientation of the chipper intake (forward or sideways) has important connotations. Row thinnings imply a largely linear method of working, and a forward oriented chipper easily receives the butt-ends of the FT lying in the row, allowing the machine to move forward at approximately the same rate as the tree is being fed into the chipper. A forward oriented chipper is mounted in front of or under the cabin, leaving the entire loadbed available for a bin, which typically accommodates around 15 m^3 (∼3,500 kg).

Fig. 6.4 Extraction of a large load of black wattle (*Acacia mearnsii*) using an agricultural tractor and tipping trailer (Photo: Talbot)

Side oriented chippers are placed behind the cabin, and take up storage space, but subject the cabin to less vibration and noise and have better mass distribution. Side oriented chippers require that the young trees have been laid into the stand perpendicularly to the strip road. A further disadvantage is that the machine cannot move forward before the tops of the trees being chipped clear the closest residual trees in the stand. The side oriented chipper is better suited to chipping tops from later thinnings where a harvester has been used and where more space is available. Maximising bin size is crucial to improving machine utilisation. Large, bulky bins can; however, cause damage to the residual stand, especially if the machine needs to reverse out of the striproad (Fig. 6.5).

In-field chipping requires some form of chip storage at the roadside landing. Tipping the chips onto the ground for later collection decouples production from transport, but results in some losses into the ground, and potential soil contamination, as well as the need for a wheeled loader or self-loading trucks (cranes with buckets) in order to move the chips to the conversion plant. Tipping the chips into a container requires firstly that the bin can be raised to sufficient height (∼2.5 m) and that the logistics around the supply and exchange of containers is well managed.

6.5.3 Harvesting Biomass from Harvesting Residues

When applying mechanised processing, residues (i.e., branches and tops) should be dropped in piles that can be collected easily and efficiently. Although over consid-

Fig. 6.5 In-field operation using terrain going chipper which feeds directly into a high tipping bin (Photo: Linddana AS)

eration of this can decrease harvester productivity as trees have to be turned and positioned over the pile (Nurmi 2007). Fewer larger piles also reduces the degree of contamination. While piles can be left on site for a winter (i.e., summer rainfall zone) to promote nutrient recycling through foliage loss, it is more rational to extract the residues to roadside landing while the forwarder is on site. For guidelines on the potential impact on the nutrient status of sites through this practice and the potential nutrient content of the various portions of forest residues, refer to Chap. 5.

Efficient extraction is highly dependent on load density, which has led to the development of extendable load beds on forwarders. Even so, achievable loads are under 50 % of mass pay-load capacity of the forwarder and longer extraction distances make collection infeasible. Laitila et al. (2005) showed a cost reduction of 10 % using an innovative combination of simultaneous residue recovery and site preparation by utilizing a forwarder fitted with disk scarifiers.

The compression of harvesting residues into bundles (e.g., slash bundling) in the stand remains in use to a limited degree but hasn't realized the expected economic benefits (Kärhä and Vartiamäki 2006). In-field bundling does require a specialized base machine (e.g., forwarder) on which the bundling unit (e.g., the John Deere B380) is mounted. In an Australian study, slash was windrowed with an excavator, which resulted in good bundler productivity (21 bundles of 570 kg per productive machine hour), but was expensive and resulted in a high level of soil contamination (8.9 %) (Ghaffariyan et al. 2011). In-field bundling also requires forwarding to roadside, implying that it needs to be carried out in conjunction with the extraction of roundwood, or a forwarder must return to the site. Bundling units can also be mounted on trucks, giving greater mobility but requiring residues to be brought to roadside. When FT harvesting is done using skidders or cable yarders, this material is simultaneously extracted to roadside. Mobile truck mounted bundlers show good potential in serving numerous production points (Spinelli and Magagnotti 2009). These units are however restricted to roadside operations.

6.5.4 Harvesting Biomass from Salvage Operations

The direct combustion of primary forest fuels in larger boilers provides an opportunity to utilize material damaged by fire, drought, wind or insects in a robust and efficient way not offered by any other industry. Burnt trees can be harvested with disc saws or with chainsaw based heads using specially hardened chains. Chipper knives would need to be switched more frequently or the material could be crushed. Most southern hemisphere exotic pine plantations have experienced losses from the *Sirex* woodwasp (*Sirex noctilio F.*) where harvesting and combustion of the trees simultaneously contributes to feedstocks and potentially counteracts the spread of the *Sirex* population. Apart from the normal complexities and dangers of harvesting windblown timber, the high level of contamination with mineral soil and stones (from upturned root mats) make the material less sought after. While volumes can be substantial, additional care needs to be taken while comminuting the material. The end user should be informed of expected higher ash concentrations.

6.5.5 Harvesting Biomass from Stumps

Stumps after harvesting represent a significant potential for increased utilization of bioenergy. But the utilization of stumps for energy in countries like Sweden and Finland is mostly constrained by ecological concerns of the physical, chemical and biological impacts on the soil (Lindholm et al. 2010). In Finland some 850,000 m^3 of stump wood was utilized in 2009, and the production is increasing (METLA 2011). The mass of the stump and coarse roots may be some 25 % of the utilized stem (Marklund 1988). For example, Fig. 6.6 demonstrates the close correlation between mass and stump diameter for Spruce stumps in Europe.

Using specially designed stump pulling and splitting heads (Fig. 6.7), harvesting in good conditions can produce 2–4 dry tonnes per productive machine hour, equating to roughly 100 stumps per productive machine hour (Athanassiadis et al. 2011). The split material is bulky and forwarding productivity rates of 7–9 m^3 per productive machine hour on extraction distances of 50–500 m were found (Laitila et al. 2008). Productivity was lower than for any other forest product, with 27 % of the time being used on unloading alone.

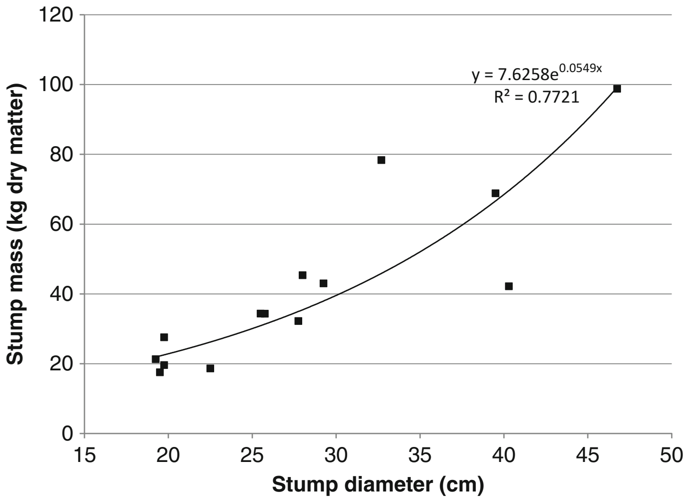

Fig. 6.6 Dry matter content of *Spruce* stumps as a function of the stump diameter at felling cut (Talbot 2010 unpublished data)

Fig. 6.7 Stump lifting device with splitting knife (Photo: Dahlin)

Stumps are normally "seasoned" by leaving them in roadside piles for some time (e.g., one year) mainly to allow precipitation and wind to erode the worst of the soil and stone contamination, and are invariably crushed with tub-grinders before or after transportation. Studies in Sweden indicate that pre-grinding and screening of stumps at landing reduces contaminant levels and loading time, and saves 15–20 % on transport costs (Thorsén et al. 2011). Apart from the volumes and generally good quality of the fuel, a considerable benefit of stump utilization from a cost perspective is that they represent an additional resource within the same procurement area. However, stumps from pine and eucalyptus dominated industrial plantations are not as easily lifted as those of spruce, and larger and more robust lifting heads would be required, depending on soil type, rooting pattern, and stump size.

6.6 Activities at Roadside Landing, Terminal or Plant

The previous section dealt with the harvesting and extraction of biomass in various forms to the roadside landing, which is almost always a discrete point between the primary supply phase (extraction) and the secondary phase of moving the material to the plant. However, the duration of time the material spends at the roadside landing varies from minutes if a “hot” container system is being used, to days, months or even years in the case of stumps. Most of the research looking at roadside storage and moisture management of biomass comes from boreal countries, where autumn and winter are characterized by large amounts of precipitation in the form of rain and snow, and where ice clumping is a problem. Few industrial plantations are located in these climate zones and local knowledge should be developed on good moisture management strategies.

6.6.1 Storage of Trees, Tree Parts or Bundles

Trees, tree parts and bundles should be stored at roadside landings in stacks that are stacked as high as possible while maintaining stability. High stacking minimizes the surface area exposed to rain (i.e., only the top is exposed) and promotes a more uniform material in terms of bulk density and moisture content. Ground contact should be broken by stacking on a simple rack of logs. Stacking butt-ends facing the landing not only promotes the run-off of rain water away from the landing, but makes for easier crane operation when chipping or transporting. These resources are stable and can be stored for long periods of time. The options from this point are roadside chipping and transport of loose chips, or transport of the material “as is” to conversion sites.

6.6.1.1 Storage of Harvesting Residues

Harvesting residues are stacked in the same way as FT or tree-parts, but given the nature of the material (no primary orientation); these stacks do not have the same natural ‘roofing’ tendency. In wetter climates it is common to cover the stack with a 4 m wide heavy duty paper from a dispenser attached to the forwarder crane. The effect of doing so varies with the time of harvest in relation to the season with only limited differences seen if the material is harvested just prior to the rainy season, whereas there are significant differences in moisture content of up to 15 %, between covered and uncovered material that are relatively dry before going into the wetter period (Filbakk et al. 2011).

6.6.1.2 Chipping at Roadside Landing

An advantage of chipping at the landing is that the harvesting/extraction and the chipping operations are not directly interlinked, and can be separated by hours or even months. This allows for a large feedstock to be built up, facilitating the use of high capacity chippers (>100 m^3h^{-1}) capable of filling a waiting truck within an acceptable time and thereby eliminating chip storage problems. Chipping material at roadside landing is the most common production method in biomass to energy chains in Europe. It can also involve chipping onto the ground or into containers. For chipping onto the ground, suitable preparation of the landing should be carried out beforehand (i.e., a clean and level site), while chipping into containers requires detailed logistics planning that synchronises container arrivals.

For chipping into waiting trucks, the challenge lies in balancing chipper productivity with truck waiting time. Chip transport trucks have loose volume capacities of 85–120 m^3 and should be filled quickly. High performance chippers capable of doing so represent large capital investments that incur expensive waiting time between truck arrivals, while low performance chippers shift the waiting time to the trucks, which can result in queuing at the landing or poor truck utilisation.

Chippers also need to be relocated from site to site. A solution to the challenges of getting this balance right is the use of chipper-trucks, with on board chippers that both chip and transport the material to the plant. The obvious benefit being that they are self-contained and highly mobile, with the drawback being the loss of payload both in terms of mass and volume due the presence of the chipper (Björheden 2008).

Recent research findings (Thorsén et al. 2011) show that self-contained chipping trucks perform well, especially in situations where their high mobility can be utilised to the full.

While gains are made in chipper productivity, the extraction of uncomminuted material (FT, tops, branches) is the least robust link in the chain. Efficient extraction of smaller trees or tree sections requires that they are pre-bunched and well presented for grapple-skidding or forwarding. Pre-bunching almost always implies mechanised felling while grapple-skidding results in higher levels of contamination with mineral soil (high ash levels) and forwarding requires that the trees have been laid in the stand and not in the strip row. FT or tree sections need to be compacted on the forwarder loadbed in order to improve the payload and maximize returns on the time cost of driving in and out of the stand.

6.6.1.3 Storage of Chips at Roadside Landing

Irrespective of whether the material was chipped in the stand and extracted to the landing, or chipped at landing, the storage of chips at roadside landing is normally a short term process but with numerous implications. As a result of the chipping and/or extracting process, the material can either be stored on the ground or in some form of bin container.

- Chips stored on the ground

  The benefits of storing chips temporarily on the ground are that there is no direct coupling with transport and that there is a large space/volume capacity. This option is good for high performing chipping production systems with transport constraints. The immediate disadvantages of chipping onto the ground are that the loading of chips requires specialized equipment or additional machinery and that some of the volume must be forfeited in ensuring that chips contaminated with soil and stones are left *in situ*. It is therefore not a suitable method when harvesting biomass from small, dispersed stands.
- Chips stored in containers

  The chips that have either been extracted from the stand and transloaded into a container or they have been chipped directly into a container at the landing. In the first instance, the availability of containers has to match the performance of the production system or a very high ‘interference’ penalty will be paid (Talbot and Suadicani 2005). Irrespective of production system, the assumption underlying this storage method is that transport is imminent. Chipping into containers with buffer capacity requires a lower performance (i.e., cheaper) chipper. Full containers left for a weekend for example, should be covered or fitted with sufficient drainage if there is a possibility of rain.

6.6.2 Storage and Handling

For all production systems, biomass needs to be stored and handled a number of times between the stump and the conversion plant. Good supply chain theory suggests that raw materials be kept in their original form as far down the chain as possible. This is to minimize early investments in the form of processing costs, and to allow the “manufacturer” more freedom in utilizing the resource right up until final conversion. The same idea holds true for biomass, though also for biological reasons. Comminuting biomass into chips radically increases the surface area, which together with high moisture content, provides ideal conditions for microbial activity. Exothermic respiration heats up the chip pile and results in dry matter loss due to the breakdown of cellulose and hemi-cellulose and even spontaneous combustion. Dry matter loss transforms directly to a loss in calorific value, and economic erosion. In addition to this, there is a growing awareness of the risks to human health of the clouds of fungal spores that emanate from stored chip piles. People in close contact with these, e.g., truck drivers, should wear respiratory masks when handling chips.

Roundwood is stable and dry matter loss is minimal in the first year after felling. Storage can take place at the point of felling, in bundles on the strip road, in piles at the landing or at the conversion plant. Initially, storage equates to drying, and freshly felled timber can dry to around 40 % moisture content (wet basis) within a number of weeks, depending on the ambient climate. FT felled and left on the ground have a steep drying profile, accelerated by transpiration from the leaves or needles. In spruce, transpirational summer drying is enough to allow the needles and fine fractions to fall to the ground during chipping or handling. This reduces the off take of nutrients from the site and reduces concentrations of corrosive elements (e.g., chlorine) in the fuel (Chap. 5).

FT, tree sections, tops or stemwood for energy can be stored in piles with or without cover. In Finland it is common practice to cover biomass piles with heavy duty paper sheeting as mentioned above. The benefit of doing this is dependent on the time of year the biomass is harvested, and for how long it will be stored. For a single summer, the drying profiles for covered and uncovered stacks are very similar, while biomass that is harvested late in the season will dry substantially faster under cover during autumn and winter (Filbakk et al. 2011).

Handling of biomass is accomplished with conventional forestry equipment as far as possible. Round wood for energy is no different from e.g., pulpwood. However, loose tops and branches are characterized by low densities and benefits can be gained from using adapted grapples that can handle high bulk loads. A residue grapple is made up of four separate grapple arms (tines) that are sharpened and easily penetrate a residue pile. In collecting harvesting residues, it is common to use forwarders with extendable loadbeds, or trailers with the capability to compress the load. For handling chips outside of a specialized terminal, either a front-end loader fitted with a large bucket or a bucket-grapple on a crane is commonly used. Due to the low bulk density, buckets can be over-dimensioned without the risk of exceeding the working capacity of the crane. At the conversion plant, a bunker below ground level allows for trucks to quickly tip a load that is subsequently evenly distributed or mixed with other forms of biomass with an over-head gantry, capable of operating continuously in two dimensions. In modern plants, these gantries operate autonomously, and also serve to feed chips into the boiler in-feed.

Chipping at the conversion plant offers considerable advantages, in that a large and powerful chipper can run consistently, and is well maintained by maintenance staff at the plant, resulting in very little downtime. The stationary chipper can be used to chip material of any size (bundles, stemwood, off-cuts, FT), and is fed and monitored by sophisticated systems, allowing it to operate around the clock. Also, the feedstock is stored in a natural and stable form, and only chipped on demand, reducing the need for covered or paved chip storage areas, and eliminating the risk of fire. If the plant is located near an urban area, noise pollution from centralised chippers can be experienced. Another disadvantage is the fact that all loose material needs to be transported to the plant for comminution. This can have implications on the potential extent of the procurement area.

6.7 Secondary Transport of Biomass

Secondary transport of biomass aims to move units of energy from source to conversion facility at the lowest cost. As a large part of transport cost is made up of fuel costs, this is synonymous with minimizing energy consumption in supply. Biomass ready for transport to the conversion plant exists in many forms with varying degrees of moisture content and differing assumptions on costs and efficiencies can give different suggestions on transport form (Tahvanainen and Anttila 2011). Biomass has a varying but generally low bulk density. For wood chips roughly 40 %, for trees and tree sections about 35 % and for harvesting residues, only 15–20 % of the load volume is solid matter.

6.7.1 Biomass Transport Truck Types

Road transport vehicles are the predominant mode of transport. Permissible loads are governed by the legal gross vehicle (or gross combination) mass and the allowable axle or axle unit mass/es. In South Africa for example, the maximum allowable mass on a single axle (non-steering) is 9,000 kg (7,700 kg on a steering axle), 18,000 kg for a two axle unit and 24,000 kg for a three-axle unit. The least of either the sum of the axle unit masses or the maximum legal gross combination mass (GCM) represents the gross legal allowable mass. The maximum permissible gross vehicle mass for South Africa is 56,000 kg. The maximum width for a vehicle exceeding a gross vehicle mass of 16,000 kg is 2.6 m. Below this gross vehicle mass the width is limited to 2.5 m. The maximum height for all vehicles is 4.3 m (FleetWatch 2012). Container trucks are popular due their versatility while truck-tractor and semitrailer configurations allow larger payloads.

A study examining 58 trucks showed a mean payload of 23,500 kg for container trucks and one of 29,164 kg for articulated trucks. The tare mass of the container trucks was 24,246 kg and for the semitrailer 16,180 kg meaning that the semitrailer is 8,000 kg lighter and has a larger load space (Fig. 6.8). Unloading times were 20.95 min on average for the former and 45.36 min for the latter (Talbot and Suadicani 2006).

Even though the bulk density of forest fuels is low, an increasing moisture content implies that less energy is transported per truck cycle (calculated as the lower heating value), i.e., at the same transport cost. However, at some stage, the total mass limit of the truck is exceeded and the load volume has to be reduced as well, drastically reducing the amount of energy being transported (Fig. 6.9). At 50 % moisture content, the semitrailer (upper line) carries 16 % more energy than the container truck (lower line) while at 55 % MC, it carries 30 % more. This is an important relationship to understand as chipped residues have a higher density than chipped stemwood (shown here) due to the heterogeneity of the material and the higher density of the branches.

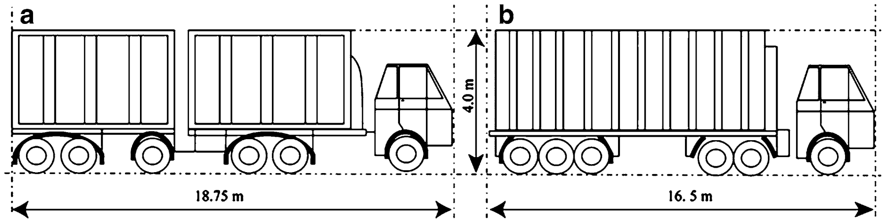

Fig. 6.8 Generic container truck carrying roughly 85 m^3 (**a**) and a semi-trailer, with a capacity of approximately 108 m^3 (**b**)

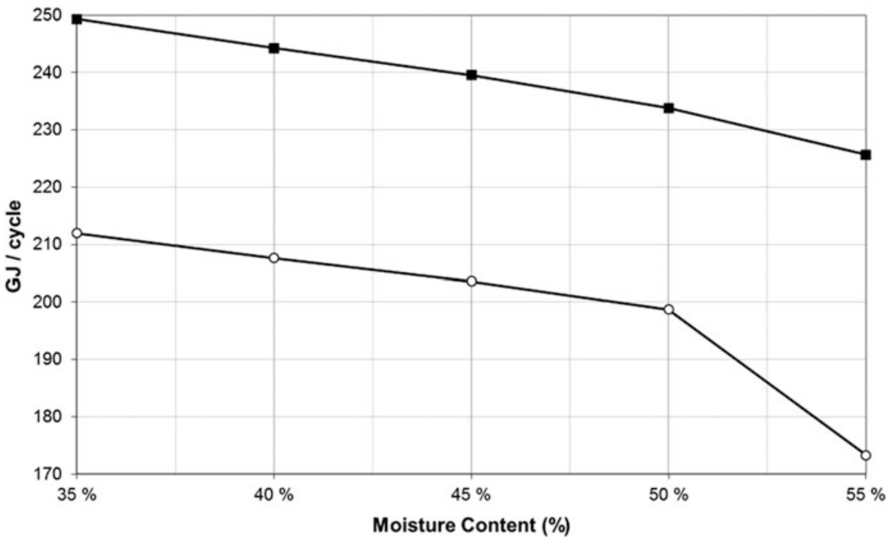

Fig. 6.9 Energy content per load transported against increasing moisture content. For the container truck (*lower line*) the gross mass is met at 50 % and load volume must be reduced to meet legislation (Talbot and Suadicani 2006)

In recognizing that increasing volumes of biomass will be transported over increasing distances in the future, efforts are being made to develop vehicles with increased volumetric and mass carrying capacities. EU directive 96/53/EC allows member states to test and adopt the European Modular System (EMS) which allows for vehicles up to 25.25 m long with a gross mass of 60 tonnes. Countries like Sweden and Finland have benefitted greatly from applying these trucks in transporting forest fuels. In South African Performance Based Standard (PBS) type rigid truck and drawbar trailer combinations are now allowed to operate, with special permits, at lengths of 27 m and 70,000 kg GCM and a payload of up to 49 tonnes (Fig. 6.10). Solely used as roundwood pulpwood vehicles currently (and normally mass limited), these PBS trucks will fulfil a specific role in biomass transport for the same reasons mentioned above.

Fig. 6.10 Loaded Performance Based Standard (PBS) truck on N2 highway, KwaZulu/Natal (Photo: RailRoad Association of South Africa)

6.7.2 Economic Considerations of Transport

The choice of an ‘optimal’ form of transport for a planned bioenergy plant is not always straightforward, and will depend on whether the enterprise already transports, e.g., pulp chips, whether all transport is to be outsourced, and whether a small or large scale operation is planned. However, some consistencies in making a rudimentary evaluation do exist. If the conversion plant is to be located alongside an existing sawmill in a plantation area, it could be acceptable to use an off-road agricultural tractor/trailer system where the typical distance is under 15 km, while if the intention is to supply a central heating plant in the next city, sophisticated haulers are required. Transport distance is not the only important factor in making the decision on how to invest. In the case below, we will show how factors like loading and unloading (terminal time), load capacity, moisture content, delivered energy price, and investment costs bear influence on a good economic solution. One solution can never be optimal for the diversity of sites encountered in forestry; however, a good solution should perform well on average.

6.7.2.1 Loose Chips

Transporting loose chips calls for as large a loading space and as low a tare weight as possible. Only if the chips are made from very fresh material will the load approach the mass restriction of the truck. The most common solutions seen for transporting loose chips are container systems (from 85 to 120 m^3), i.e. two containers loaded

Fig. 6.11 Container truck exchanging chip containers at landing (Photo: Talbot)

on a rigid truck and drawbar trailer separately, or on semi-trailers drawn by a truck-tractor (Fig. 6.11). The reason that containers remain popular despite their high tare weight is that they can be exchanged quickly at the chipping site, reducing waiting time on both the truck and the chipper. The use of standard freight containers (40 m^3) can be justified by the advantage they offer of being utilisable by a large number of transport contractors; enabling a more flexible local supply chain, where the number of containers or trucks can be varied to meet individual operations. They can also be used for transporting other material during periods of lower demand.

6.7.2.2 Loading and Unloading

Bulk trailers take on a number of forms. Rigid trucks with a tipping bed can be used without a trailer, but transport a limited volume. These trucks are compelled to wait during the loading process, but are agile on poor forest roads and have a short unloading time. For longer chip transport, semi-trailers fitted with reciprocating slatted floors, such as the Walking Floor™ trailer, or side tilting designs, can be used successfully. Articulated trucks can have problems on winding or steep roads, but benefit greatly from their superior load capacity. Semi-trailers and drawbar trailers can be exchanged at the landing, or the truck can wait to be filled. This requires matching with a high production chipper. Side-tipping trailers have minimal offloading times, but require specialized receiving bunkers that run the entire length of the trailer. End-loading trailers can unload into more commonly available bunkers. Chipper-trucks (fitted with own chipper) have reduced transport capacity but have high mobility in that they are not dependent on other machines and work well in areas with a higher number of smaller landings.

6.8 Managing Biomass Trade and Supply

The development of a good business process model for biomass supply is something that many enterprises see as a challenge. More specifically, the measurement of the biomass, the calculation of the heating value, and the varying lead times (from hours to years) are elements that many supply chains wrestle with. In the following section, some fundamental business process structures are presented.

6.8.1 Owner Supplies Directly to Plant

For a small forest owner, this is the simplest form as the forest owner internalises all costs and delays in preparing the biomass for delivery. The basis for measurement is weighbridge mass, corrected for moisture content (see generic description of this below). If the forest owner has utilised contractors for harvesting or transport, the bill for this can be settled in conjunction with conventional harvesting on a volume basis (m^3 – solid) costs using a suitable biomass expansion factor (BEF) which is multiplied against the roundwood harvest. The transport operator can be remunerated directly from the weighbridge bill. The forest owner incurs the costs at the time of each operation.

For a forestry company delivering to its own energy plant (e.g., CHP plant at saw-mill), the model would depend on the accounting processes between internal business units (e.g., harvesting business unit is separate from CHP business unit). From the energy conversion facility's perspective, dealing with a large number of small forest owners (and other suppliers) is complex given that supply is almost impossible to schedule, there is little information on what is in the pipeline, variation in material and its properties can be large, and guarantee of delivery uncertain. These (considerable) disadvantages will be reflected in the price.

6.8.2 Owner Supplies Through Cooperative (Forest Owners Association)

Many forest owners are already members of cooperative organizations that provide services (forest management, harvesting and logistics) and access to market channels. Also, some bioenergy conversion plants create specialized cooperative units which manage the longer term procurement of biomass on their behalf (or a group of forest owners invest in a bioenergy plant). Irrespective of the structure or origin, this business process model is characterized by the undertaking to maximize the interests of their members.

In this case, the forest owner can either supply directly (as in case above) or can choose to leave the procurement process to the cooperative. In the latter case, the cooperative carries the costs to the contractors in the supply chain. Advantages of cooperative supply are: (1) that the interests of the forest owner are seen to; (2) that the cooperative can incubate good contractors and streamline business processes; (3) economies of scale and benefits (e.g., speed of payment) of being a large and consistent supplier to an energy plant; and (4) that dividends, bonuses, or revenue adjustments can be made retrospectively.

6.8.3 Third Party Supply

In this model, a contractor or broker (or other 3rd party) purchases the biomass and undertakes the necessary activity in feeding it into the downstream supply chain. Volumes/energy content must be determined on site at, or after, harvesting. Once again, established BEF can be utilised or the volumes can be estimated from pile dimensions and local guidelines. The advantage for the forest owner is one of a small (but somewhat uncertain) income on site and no responsibility for costs to contractors and uncertainties of supply. The benefit to the energy conversion plant is a longer term relationship with a single supplier representing many forest owners.

Standard models for determining energy content in the supply chain are given below:

6.8.3.1 At the plant

Ultimately the bioenergy plant determines and pays for the energy content of biomass being delivered though its gates. This is done for chips as follows:

1. The (registered) truck driver notes the origin of the biomass on the incoming weighbridge bill, which includes a timestamp. The registration of trucks includes the details of the supplier for whom they are transporting.
2. The driver (or staff member) takes a bucket sample of the chips while they are being poured into the chip bunker – ensuring it is as representative as possible. Some plants are equipped with fully automated sampling devices that bore into the load while still on the truck.
3. The sample is placed in a drying oven together with the weighbridge bill
4. After 24 h at 105° C, the dry matter content of the load is calculated and remuneration to the supplier is affected.

When it comes to other forms of biomass (FT or residues), it is not possible to make accurate estimates of energy content before the material is chipped and dried. With well-developed delivery systems, e.g., from uniform plantation forestry, conversion figures including norms and standard deviations can be developed rapidly and improved on with time. Here, the supplier is paid a value derived from e.g., mean moisture content per specie and season.

6.8.3.2 At the landing or terminal

Solid content conversion rates for stacked harvesting residues, FT, or roughly debranched stems should be developed regionally and according to species. Apart from errors arising from edge effect, a good relationship can be obtained between running metre of stacked volume and solid volume. A simple way of developing such conversion rates is by chipping the stack into a container of known volume. The dry mass of the chips arising from this process is then compared with the dry mass of the tree species in question in determining solid volume equivalents. It should be remembered that high branch content will yield a dry mass higher than the mean for stem-wood for the same species.

6.8.3.3 On Site (pre- or postharvest)

On site estimation of biomass involves an enumeration of standing trees or residues/stumps after harvesting. Methods of ensuring reliable estimations are given in Chap. 3. Some adjustment needs to be made as varying percentages of the measured volumes are utilisable. For harvesting residues after the CTL method, about 70 % of volume is typically recovered.

6.9 Managing Feedstock Supply and Supply Cost Curves

Whether planning the location or capacity of a new plant, or supplying an existing plant, the procurement manager needs to have a good idea of the cost profile for feedstock supply. The location of the resource in relation to the conversion plant is more or less fixed, with annual supply deviations depending on the harvesting or thinning plans. A relatively simple and visually cognitive way of representing the economic availability of the resource is to develop a marginal supply cost curve. This implies deriving and plotting the cost of the last most expensive resource against the cumulative volume acquired up until that point. The cost is a composite figure, which includes harvesting, storage, handling and transport of each biomass type, and from each geographic source point, to a given destination, commonly the plant gate. This means that each resource point (stand) is handled individually in terms of harvesting method, yields, sequencing etc. Such an overview can easily

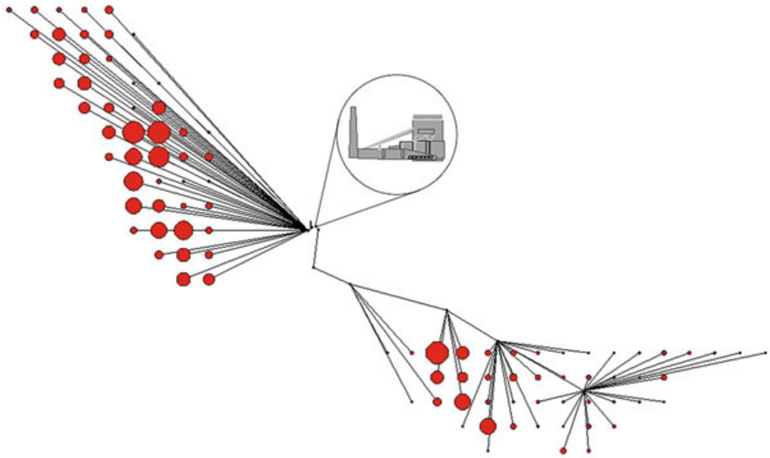

Fig. 6.12 Schematic oversight of the relationship between biomass volumes and transport distances in an extensive woodland

be constructed and maintained in a spreadsheet, although the accuracy is fully dependent on the cost estimations made underway. These can be based on rough estimates e.g., Fig. 6.12 (where each circle represents the volume available in a 1 km^2 grid cell and the lines represent distance to the plant) or modelled in detail in GIS (Möller and Nielsen 2007). The following section provides a step by step guide on how to develop such a curve.

Developing a supply cost curve for managing biomass feedstock

- Step 1. Using a spreadsheet, list all the sources, including either the net energy content or the tonnes of dry matter available as the primary unit.
- Step 2. Estimate a harvesting and transport cost for each source. This can vary considerably depending on the kind of operation (early thinning vs. clearfelling), the terrain, the anticipated transport method and distance.
- Step 3. Sum these costs in a new column and rank the spreadsheet according to increasing delivered cost.
- Step 4. Generate a new column showing the cumulative quantity of energy (sum of all preceding energy quantities). You now have the necessary data for plotting the marginal supply cost curve. However, it is important to know the mean cost as well as the marginal cost.
- Step 5. The mean cost is more complex to calculate as it requires the sum-product of all preceding energy quantities and their respective prices to be divided by the cumulative volume. We use a simpler method to get there: calculate a total cost column (GJ * unit cost) and then sum this up in a cumulative cost column. The mean cost is then the cumulative cost divided by the cumulative volume. Now the supply cost curve can be plotted as in Fig. 6.13).

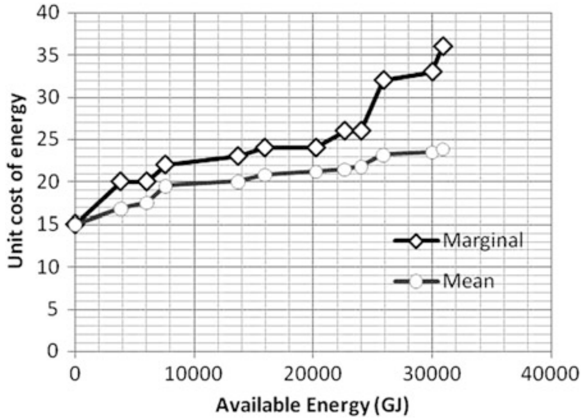

Fig. 6.13 An example of marginal and average value supply cost curves

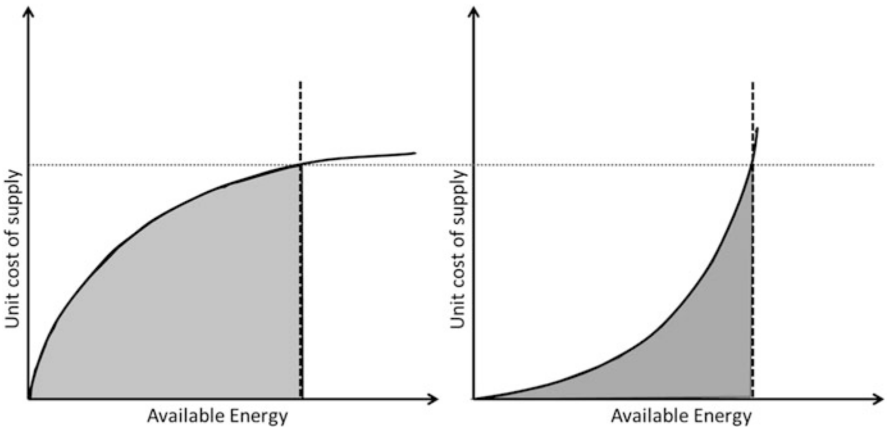

Fig. 6.14 Mean (and marginal) cost curve comparison. The *greyed* area represents total cost and marginal cost is provided by the curved line. The mean cost for the procurement area on the *left* is significantly higher than that on the *right*, despite their having equal marginal costs

The resulting plot from step 4 provides a marginal cost of supply curve. The procurement manager can read what volume is available at what price directly from the curve. However, what is more interesting for procurement management is the mean cost of supply, as managers will normally be working from an operational budget. The manager might have settled on a maximum marginal cost that he/she is willing to pay a supplier, but this might not be the best course of action as is explained below.

The shape of the cost curve function (whether convex or concave) in arriving at the same marginal cost for the same quantity of energy, could imply two vastly different mean costs (Fig. 6.14). The shaded area represents the total cost of supply, i.e. incremental cost multiplied with the incremental quantity. In this example it is easy to see that two very different mean costs are arrived at when the total cost is divided by the total volume. Even if the marginal cost is the same, the mean cost can be quite different as the shapes of these two cost curves illustrate. The mean cost is represented by the shaded area (Fig. 6.14).

There are a number of ways of extending the utility of these curves. Including a code for the present state of the biomass (e.g., loose residues, bundled residues, chipped residues) and/or the stage of where the biomass is in the supply chain (planned harvest, harvested, at landing, at terminal) gives the procurement manager insight into the dynamics of the supply pipeline within a given time horizon, whether it be a week or a year. This means that the manager is able to negotiate prices, or incur heavy costs, in procuring biomass from specific suppliers or sources without compromising the budget.

6.10 Conclusion

This chapter described the possible sources of bioenergy from forests, early thinning, harvesting residues, salvage operations and stumps. Furthermore, the options of collection, extraction, haulage and comminution have been discussed. It has been shown that the place of comminution within the supply chain is decisive for the design and cost-efficiency of this bulky, low value commodity with limited potential for transport efficiency gains. One rule of thumb is that the shorter the transport distance, the later comminution should be performed in the supply chain. On the other hand, for long transport distances and a bulky assortment, comminution could be carried out in an earlier stage of the supply chain in order to decrease transport costs. In most cases the supply is not made up of one chain, but consists of a network of supply chains, where the challenge is to utilize machinery where it is best suited and to minimize costs. Utilising supply cost curves can provide insight into the most suitable supply chain for a particular situation.

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