Forest residues: Harvesting, storage and fuel value

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FOREWORD

A feature of COFORD's research programme has been the recognition that an enormous potential exists in Ireland for the development of alternative, renewable, wood-based energy systems. Wood energy generation has distinct advantages over other conventional fuels, especially in the light of Ireland's commitment to reducing its CO_2 emissions under the Kyoto Protocol. Furthermore, the growing Irish forest industry is well-suited to the development of a wood fuel industry, specifically tailored to Irish conditions.

This work that is reported was highly innovative. It sought to develop a method for the harvesting of forest residues left on the forest floor following harvesting. A number of systems were reviewed in countries such as Finland and Sweden, where forest residues are already used to a significant and growing extent as a fuel for combined heat and power generation. The project involved work not just on residue collection - a prototype forest residue bundler was designed for Irish conditions - but examined other important and practical issues such as the handling, drying and storage of residue bundles. In addition, valuable work was carried out on the energy value of forest residues.

The work is valuable not only in the results obtained but in the general background it outlines as far as the use of wood for energy is concerned. As we have indicated, wood energy has the potential to make a significant contribution to achieving national targets for renewable energy and reduction of greenhouse gas emissions. There is a rapidly increasing area of private plantations in this country, many, if not most, of which would benefit from early thinning. These thinnings are an ideal wood fuel source. Harvesting residues, as outlined in this report, are another potential source. Indeed a wood fuel assortment could be a feature of all forest harvesting in the future.

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1. SETTING THE SCENE: ENERGY IN IRELAND AND WOOD AS A RENEWABLE ENERGY

Wood has been a convenient and renewable fuel since humans first used fire for cooking and heat. Even to the present day in the Alps and other mountainous regions, home heating uses wood from local forests, dried naturally under shelter. However, in other parts of the globe, excessive wood fuel harvesting has had devastating consequences on forest cover and regeneration. This is particularly the case in parts of Africa and Asia. Closer to home, the bare, karst limestone of the Burren in Co Clare may be the result of overgrazing and burning of natural vegetation by early farmers several millennia ago.

Until the very recent past a great deal of the earth's carbon was stored in coal, oil and gas deposits. Nowadays, many developed and emerging nations are increasingly dependent on such fossil fuels for heat and energy. Ireland is no exception, in 1996 fossil fuels accounted for 88% Ireland's total primary energy requirement (TPER) -75% of which was imported. It has been estimated (Buckley 1997) that if current trends continue, 93% of TPER would imported by 2010. This is not a sustainable policy, as in many cases these fuels are sourced in politically and socially unstable regions. Furthermore, major increases in fossil fuel prices can have a serious negative effect on the Irish economy and living standards.

There is a strong case for the development of alternative, renewable energy systems based on wood and other sources. There is good reason to believe that there will be socio-economic benefits to be gained from their use. One Euro spent on domestic fuel and labour is likely to benefit the economy more than the equivalent spent on imported fossil fuel of the same energy value. The development of a renewable energy industry in Ireland will certainly help to reduce dependency on imported fossil fuels and may also generate additional employment.

A further positive aspect of the use of wood for energy generation is in combating the rise in atmospheric CO_2 levels. There is international speculation and concern that the increase in levels of CO_2 in the atmosphere, due to the greater use of fossil fuels, is causing global warming - the 'greenhouse effect'. In response to these concerns a number of developed nations are committed, under the Kyoto Protocol to the United Nations Framework Convention on Climate Change, to efforts to stabilise CO_2, and other greenhouse gas (GHG) emissions to the atmosphere. Ireland is committed to holding its CO_2 emissions at 13% above the 1990 level, by the first Kyoto commitment period 2008-2012. However, predictions (Buckley 1997) show that if the current rate of increase is maintained, CO_2 emissions will be 34% above the 1990 reference level by the first commitment period, and 20% above by 2000. The National Climate Change Strategy shows these predictions to be relatively accurate, with 1998 levels at 18% above 1990 levels and levels for 2010 projected to be 37% above (Department of the Environment and Local Government 2000).

Renewable energy sources are being sought which will meet the requirements of sustainability and of carbon balance. Energy from such sources, of which wood is one, has many important advantages. As energy sources they are environmentally neutral in terms of the 'greenhouse effect'. They are renewable, in contrast to fossil fuels. Trees use atmospheric CO_2 and water to manufacture sugars and thence wood. When converted to energy, the carbon is released to the atmosphere. However, as long as the rate of planting exceeds, or equals, the rate of felling there will be no net gain in atmospheric CO_2 concentrations over time.

The project described in this report sought to assist in developing the use of wood fuel in Ireland. In particular, it focused on developing a method for the economic use of forest residues as a low-grade energy source. The use of wood and forest residues as a fuel for heating and power generation is well established in Austria, Finland and Sweden. The forest industry in Ireland is growing rapidly and there is potential for the development of a wood fuel industry specifically designed for Irish conditions.

2. THE FOREST RESIDUE RESOURCE

In Ireland, forest residues are usually left on the forest floor after wood harvest. Occasionally some of the larger waste wood is removed as firewood for domestic consumption but this does not occur on any scale. It has been estimated that the amount of forest residues varies from 50 to 100 odt/ha (oven dry tonnes) depending on species, age, site type and wood assortments harvested (Mitchell and Hankin 1993). The total annual residue resource that is currently available has been estimated as between 300-400,000 t (Bulfin and Rice 1995). About half of this may be available for harvest. In energy (electricity) terms a study on the total renewable energy resource in Ireland (ESBI 1997) estimated that residues could contribute 26 MW in 2000 and 145 MW by 2020 (at a cut-off price of 5.5p/kWh).

A significant factor in assessing the residue resource is the size of the material (harvesting is normally to a top diameter of 70 mm) and the amount of dead and waste wood which is left on the site after extraction. Some of the material in the present study was up to 125 mm in diameter and over 4 m in length. On some sites in Co Limerick and Clare, it was estimated that up to 40% d.m. (dry matter) of harvestable residues was over 25 mm diameter.

3. OBJECTIVES

The project set out to explore the potential for the development of forest residues as a fuel source in Ireland. The first part of the project involved a literature review, which identified the key issues in the wood fuel supply chain. Based on the findings of the review it was decided to investigate the technical feasibility of bundling forest residues.

Specifically the objectives of the second part of the project were to:

1. develop and test a mobile bundling machine;
2. analyse the effects of bundle size and density;
3. study the behaviour of forest residues when bundled and left to dry naturally;
4. analyse the optimum drying period, time of year of production and drying position;
5. analyse variation in moisture content, calorific value and dry matter losses in bundles;
6. utilise the results in the design of a mobile forest residue bundling machine.

This report covers the second part of the project. Copies of the literature review are available on request from COFORD.

4. BACKGROUND TO THE PROJECT

4.1 Wood harvesting in general

Tree felling and delimbing in Ireland has become increasingly mechanised. Harvesting heads are fitted to purpose-built machines or on excavators converted for harvesting (Figure 1). These are able to produce lengths of delimbed wood to reasonably consistent dimensions.

More advanced harvesting heads are able to record production by measuring diameters and lengths, and number of pieces processed. While delimbing, the normal practice is for the harvester to place the residues (tops and branches) in front of the machine to form a brash mat, while cut-to-length wood is placed on either side of the mat (Figure 2). Forwarders extracting wood travel on the brash mat, which provides better traction while at the same time protecting the soil.

Other systems involve the extraction of the whole tree to a roadside tree processor which delimbs, debarks, chips and cuts to length at one location. Whole trees can be brought to the roadside by forwarder but this process may be more expensive than cable extraction systems which are sometimes used. Cable extraction is more suitable for steep slopes, or on soft terrain with access difficulties.

4.2 Forest residues - technical and economic barriers to their use for energy generation

A review was undertaken by Hoyne (1996) of the wood fuel industry with a view to identifying barriers to, and opportunities for, development of wood energy. The review identified the growth in the use of forest residues as a fuel source in Finland and Sweden where considerable work had been done with wood chips. They were, and remain, the most common form in which wood fuel is used for combustion and gasification.

Hoyne (op. cit.) identified a number of problems which contributed to the relatively high cost of forest residues as a feed-stock for power generation. In particular, their bulky nature, and handling difficulties, either loose or as chips, were drawbacks. He concluded that under Irish conditions forest residues had difficulty in being accepted as an alternative energy source against a background of historically low oil prices and the concern over the removal of nutrients from poor soils.

4.3 Economics of harvesting and handling residues

Forwarder extraction of unsorted, uncompacted forest residues is usually uneconomic as the bulky nature of the material results in low payloads.

Figure 1: *Hymac excavator fitted with a harvesting head placing wood lengths alongside residues which form a brash mat under the tracked vehicle.*

Figure 2: *Brash mat of fresh forest residues at Murroe, Co Limerick.*

A typical 8 t forwarder would only extract 2-3 t of residues in the uncompacted state (Brunberg 1995). Therefore more productive systems are needed.

4.3.1 Chipping

The low bulk density of loose residue material (150 kg/m^3) (Larsson and Norden 1982) results in average lorry loads of 15 t, only half the legal load limit. Haulage is therefore a major factor in the overall cost of delivered wood fuel. While wood chips are less bulky (220 - 265 kg/m^3) they can be difficult to store unless dry. Self-combustion and fungal growth leading to operator health problems (such as farmer's lung) are the main hazards. In addition to the these drawbacks chipping has two other disadvantages:

1. chips are bulky and require specialised machinery to produce and transport;
2. in many cases, residues are contaminated by soil and stones which can cause damage to the chipper.

Chipping systems have been developed mainly in Finland and Sweden. One currently popular system is terrain chipping. A machine similar to a forwarder, with a mounted tipping tank for storing chips moves through the site. A crane is used to feed residues into the chipper from where chips are blown into a storage tank. When the tank is full a shuttle vehicle comes alongside and brings the chips to a roadside stockpile. In some situations the chipper also brings the chips to roadside.

The start-up costs for a chipping unit would include purchase of a chipper, conversion of at least one forwarder to shuttle duties, a loading shovel, trucks with high sides (adapted for forest roads) and suitable storage areas either in the forest or at a depot. In the event of a rise in the price of oil the cost of operating chippers will rise in tandem. Not alone will the fuel cost per tonne harvested rise, but the capital cost of specialised machinery may also rise.

4.3.2 Bundling

Hoyne (1996) examined the use of harvesting and handling systems other than chipping, that have the potential to improve the cost competitiveness of residues as an energy source. In particular, he investigated the use of bundling in Sweden and concluded that it had potential as a system to harvest and handle residues. The key drivers behind the bundling concept are:

- to increase the bulk density of the material being transported and hence a reduction in transport costs;
- compact, uniform bundles are easier to handle and store than loose residues;
- material stored in bundles appears to dry sufficiently to improve its fuel quality;
- the requirement for new machinery is minimised as existing forestry equipment can be utilised for handling and transport.

Although the systems under development in Sweden and other countries have merit, it was concluded that it would not be possible to simply replicate such systems in Ireland. There was a need, therefore, to develop a system which was applicable under Irish conditions.

5. POTENTIAL USE OF BUNDLING, DEVELOPMENT OF DESIGN SPECIFICATION

5.1 Potential use of bundling

The literature review referred to found that bundling of residues was potentially competitive with chipping and offered some possible advantages. Large bundles could be handled by conventional machinery. {For example, a logging truck could be easily loaded and unloaded with bundles whereas it would need special sides and a grapple to load and transport chips (Figure 3).} Bundle density could be as good as or even better than chips and have the advantage that bundles could be handled more cost-effectively. While chip piles have a bulk density of 220-265 kg/m^3 (see above) similar values have been achieved with compacted logging residues (Carlsson et al. 1980).

The most likely end use of forest residues was considered to be heat energy generation, through either combustion or gasification. The efficiency of such processes is affected by the moisture content of the material, as water must be evaporated during the conversion process. Conversion efficiency will therefore increase as the moisture content of the material decreases. Forest residues stored loose in the forest will dry over a period of time (Jirjis and Lehtikanga 1993). It was hypothesised that bundled material would also dry naturally when stored. In addition, it was thought that material bundled at the end of summer {20% m.c., wet basis (w.b.)} would be capable of withstanding storage over winter without much deterioration. It was proposed to explore this concept with covered and uncovered bundles. It also was proposed to determine the rate at which bundles dry once the weather improves in spring and summer. Reducing the moisture content of the material using natural drying would help to increase the efficiency of the conversion process and hence reduce costs.

At the outset of the project, it was not envisaged that bundling of residues would replace chipping. It was considered, however, that bundling might have some advantages where the residues were contaminated by soil, extremely wet (50% m.c., w.b.) or needed to be moved from the site some time before use, thus necessitating storage.

5.2 Development of the design specification for bundling

Hoyne (1996) cited preliminary trials that had taken place on fairly long thin bundles (4.0-5.0 m long and 0.4 m diameter). These appeared to have been impracticable (Hansen 1978, Carlsson et al. 1980). Some tests in uni-axial, lateral compaction had also been conducted (Guimier 1985) but it was quite difficult to see how these could be used in machine design. As a result of Hoyne's (op. cit.) work, an hypothesis was developed that bundles, somewhat similar to those produced from hay, silage and straw,

***Figure 3:** Bundles of forest residue being unloaded from a wood haulage truck.*

might be a suitable medium for transport and storage of forest residues. Moreover, reduced comminution prior to storage might lead to lowered risk of self-combustion and lower levels of fungal growth as compared with chips.

As stated in the Objectives, one of the primary goals of the project was to demonstrate that forest residues, of the type commonly found in Ireland, could be successfully compacted into bundles. In developing a specification for such bundles it was necessary to consider the material, the machinery available for compacting and handling residues, drying behaviour and mould growth, and end-use.

Bales and bundles are normally produced as rectangular prisms or cylinders. Rounded bundles have a smaller circumference for a given sectional area, and are considered to be more dimensionally stable. Bales with triangular or rectangular cross sections have a larger circumference/volume ratio; there is a natural tendency in such solids to expand to minimise internal stresses.

The handling and harvesting of forest residues is affected by the orientation of the material on the forest floor, which is determined by the harvesting method that is used. Motor-manual harvesting methods tend to leave the material dispersed and randomly orientated. Mechanical felling processes usually leave the residues in brash mats, as outlined. Residues in the mat are usually orientated in a particular direction and are often contaminated by soil. Hoyne (1996) determined that any new harvesting system should ensure that the handling of the residues is kept to a minimum. Furthermore, it would be advantageous to have residues orientated in the brash mat, or similar piles, to improve handling.

In developing the design specification for the bundling machine, barriers to potential commercialisation and the high capital cost that might be associated with high levels of automation and power consumption were considered. Experimental work with a heavy, expensive, refuse baler in Sweden, which later became the 'Bala' baler was noted (Bala 1995). Thus, it was decided to try to develop a machine which was simple, consumed a minimum of power and was compatible with existing haulage equipment.

In relation to having a low power consumption, it was proposed that a machine that packed the residues in a (generally) parallel orientation might be best. This was based on the premise that breaking or cutting residues, to form a bundle would consume additional power and add complexity. It also hypothesised that efficient packing of the material would reduce the need for a high compaction force and thus result in a lighter machine.

These considerations led to the development of the following specification for the bundles:

1. *shape:* cylindrical with residues orientated along the main axis;

2. *length:* as long as possible, within the constraints of handling and haulage. On Irish roads a load width up to about 2.4 m is generally acceptable, provided no loose material protrudes beyond this, thus it was decided to have the bundles 2.4 m long;

3. *diameter:* such that logging equipment would be able to grip the bundle, 1.8 m appeared to be the maximum, but it could be as low as 1.0 m;

4. *mass:* should not exceed 80% of the lifting capacity of forwarders at 2 m extension beyond the wheelbase of the machine, approximately 1 t. A range of 0.5 to 2 t was assessed during the trials;

5. *dimensional stability:* tied or strapped to maintain the shape of the bundle and to facilitate handling by conventional logging grapples.

It was felt that a specification for the prototype should also allow a range of bundle sizes and types to be made. While such versatility could lead to complexity and higher cost, results from the manual bundling investigation gave workable estimates of the range of bundle sizes that could be examined.

The following parameters were used in the design of the prototype bundler:

- *loading:* residue material to be loaded using a conventional logging grapple or similar equipment adapted for residues;

- *orientation:* residue orientation important to allow good compaction, machine to facilitate orientation of randomly arranged material;

- *compaction force:* the machine to exert a radial force on the bundle of at least 150,000 N/m^2 (see Section 5.2.1);

- *bundle ends:* residues were loaded and compacted radially, consideration to be given to the need to trim and/or compact the ends of the bundles to provide a tidy bundle to facilitate stacking and storage;

- *strapping:* bundle needed to be constrained to retain its shape and degree of compaction, a strapping arrangement to be devised to hold the bundles in place during storage and handling, the unit cost of such straps to be kept low, and made to last for up to one year and be compatible with combustion technologies;

- *mounting:* machine capable of being mounted onto an existing forwarder with the minimum of modification to either component, capable of being mounted and removed rapidly;

- *gross weight:* machine, with one full bundle, to be within the capabilities of the forwarder in terms of both weight and stability;

- *overall height:* height restricted to facilitate loading of residues by grapple arm and need for road transport on a low loader (to be within the clearance height of most bridges) - a maximum of 3.5 m was initially proposed;

- *automation:* was considered but was not a priority for the prototype, however, to be capable of being operated from the forwarder cab, but acceptable to use manual fitting of restraining straps;

- *safety:* consideration was given to the safety of operatives and observers;

- *durability:* the machine was designed as a prototype and whilst it was robust, its working life was of the order of some hundreds of hours;

- *instrumentation:* no need for advanced instrumentation on the machine but an indication of hydraulic pressure desirable to estimate compaction forces;

- *energy use:* energy requirements for the handling, baling and bundling processes to be kept as low as possible (taking into account the low energy density of residues).

5.2.1 Establishing compaction forces

Following on the considerations outlined it was decided to develop a machine capable of making bundles with diameters ranging from 1.2 m to 1.8 m, 2.4 m in length. The magnitude of the force required to compact well oriented residues and the degree of volume reduction which might be achieved were unknown. An experiment was designed to determine the forces required to constrain and compact residues. Previous workers (Guimier, 1985) had made compaction samples but the data published did not appear to be applicable where radial compaction was to be used. An experimental rig was designed based on a simple compaction framework, 2.5 m square (Figure 4). Green residues were placed in the frame, wrapped and secured with a number of bands. These were tensioned manually using a ratchet and lever. The force required was measured as the size of the residue bundle was reduced. Calculations of the band force and the mean diameter enabled the pressure exerted by the bundle to be estimated. A linear regression was fitted which accurately described the relationship between the radial pressure applied and the volume reduction ratio (VRR).

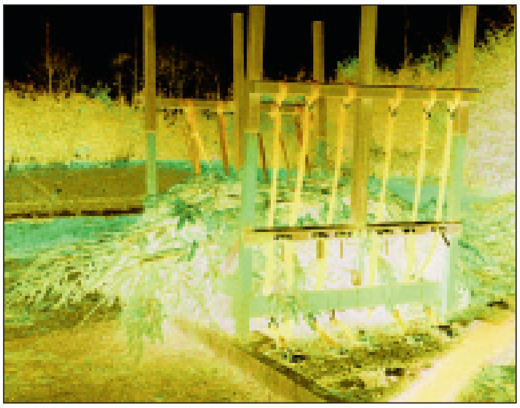


Figure 4: *Manual bundling rig with strapped specimen.*

Data from the manual bundling experiments were used to determine the amount of energy required to compact the residue material. At a particular point in the compaction process, at an applied pressure of 105 kPa and a volume reduction ratio (VRR) of 0.63, the total energy consumed in making the bundle was 24 kJ. The bundle had a volume of 2.5 m^3 and a dry bulk density of 110 kg/m^3, which equates to an energy content of 10 kJ/m^3. This gives an energy requirement of 120 J/kg for an initial bulk density (dry) of 80 kg/m^3. Thus, the energy needed to compact a 1000 kg bundle to a VRR of 0.6 using the specified bundler could be up to 120 kJ.

Guimier (1985) recorded tests on a number of machines for compacting residue materials. Using a VPI baler developed in the US, the energy requirements were 590 J/kg (0.59 kJ/kg) to produce bales with a green bulk density of 300 kg/m^3 (VRR = 0.5) from spruce residues. This was regarded as a conservative estimate (Guimier 1985). Guimier also reported data from Fridley (1981) of 1.18 kWh/t (4.3 kJ/kg) required to compact (140 kg/m^3) bales using a modified Vermeer 605F hay baler (VRR unknown). This figure is quiet excessive when compared to data from other trials. It indicates that, as predicted, compacting material radially into a bundle form requires less energy than methods which bend or break the material to form bales.

6. MACHINE DESIGN, BUILD AND OPERATION

6.1 Design

6.1.1 Location of the bundler and mounting on forwarder

A number of locations were considered for operating the bundler. Initially, it was thought that the prototype might operate at the roadside (possibly on a low-loader) and be fed by a forwarder. As the project evolved it became clear, however, that roadside work was unrealistic, and not necessarily cheaper, as it involved additional tractors, cranes and low-loaders. The emphasis was, therefore, on a design which could be adapted to fit onto a forwarder.

The final prototype design (Figures 5 and 6) had a flat base. This was a compromise based on the original roadside concept and the fact that the shape of forwarders available to the project varied considerably.

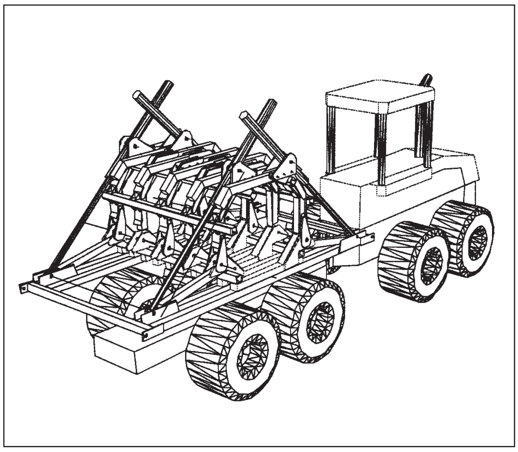


Figure 5: *CAD model of the final concept, closed position, on a forwarder.*

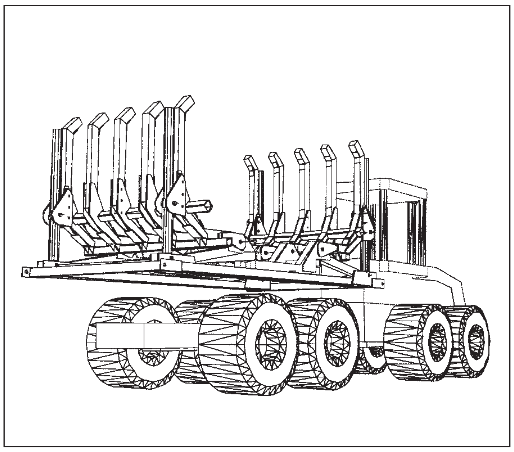


Figure 6: *CAD model of the final concept, open position, on forwarder.*

6.1.2 Orientation on forwarder

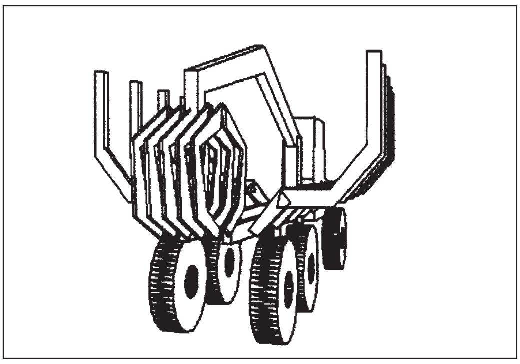
The prototype bundler had to comply with the tight specifications outlined and fit within the space normally occupied by the wood load on the forwarder, as well as producing a bundle of given dimensions.

At first it was proposed to have the bundler aligned longitudinally (Figures 7, a and b) with respect to the forwarder chassis. This required loading residues parallel to the fore-aft axis of the forwarder. Compaction was to be achieved by side arms or frames that would fold-in or otherwise move to form the bundle. The side arms, when extended, would increase the overall width of the forwarder and bundler to approximately 4.2 m. While the arms would be folded during transit there was the probability that they could become extended. Furthermore, with this arrangement of the bundler the hydraulic rams would have to extend beyond the side of the forwarder chassis.

As a result of these considerations an alternative, transverse orientation of the bundler super-structure was examined. The length of the bundle in this orientation (1.8 m) corresponded well to the allowable width of a forwarder and enabled the natural length of the payload area to be used for folding wings or arms (Figure 7, c and d). The support structures for compacting the bundles could also be easily accommodated without exceeding legal load restrictions. A number of alternative arrangements of the bundler in this orientation were evaluated before the final design was developed. The final concept arrived at was similar to that of two hands being clasped so that the fingers intermesh.

6.1.3 Compaction ratios

It was considered desirable to compact the residues in one movement of the folding mechanism so as to maximise productivity. It was important, therefore, that the 'open' position allowed a full load of residues to be placed quickly and easily into the bundler with good vision for the operator. The objective was to get a compaction ratio of at least 3:1. Clearly, an open-topped space was easy to fill but as it closed to compact the residues, there was a danger they would be forced out through the top of the bundler as the arms closed. It was important to ensure, therefore, that the side frames interlocked to form an enclosed space early on during the compaction cycle. The closing mechanism, sectional area and compaction ratio are shown in Figure 8. It was envisaged that the residues would become



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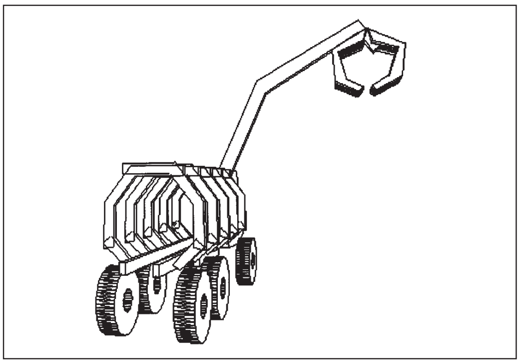

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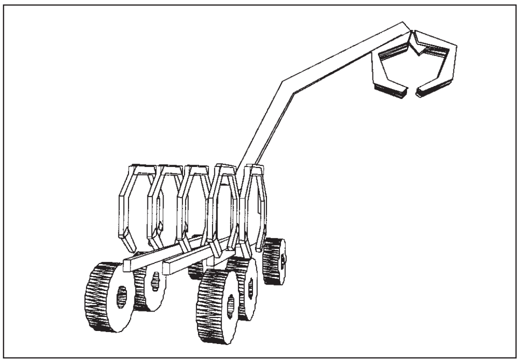

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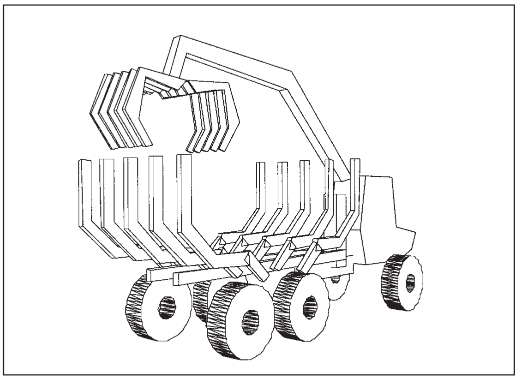

d

Figure 7: *Bundler orientation;*
a and b – longitudinal, c and d – transverse.

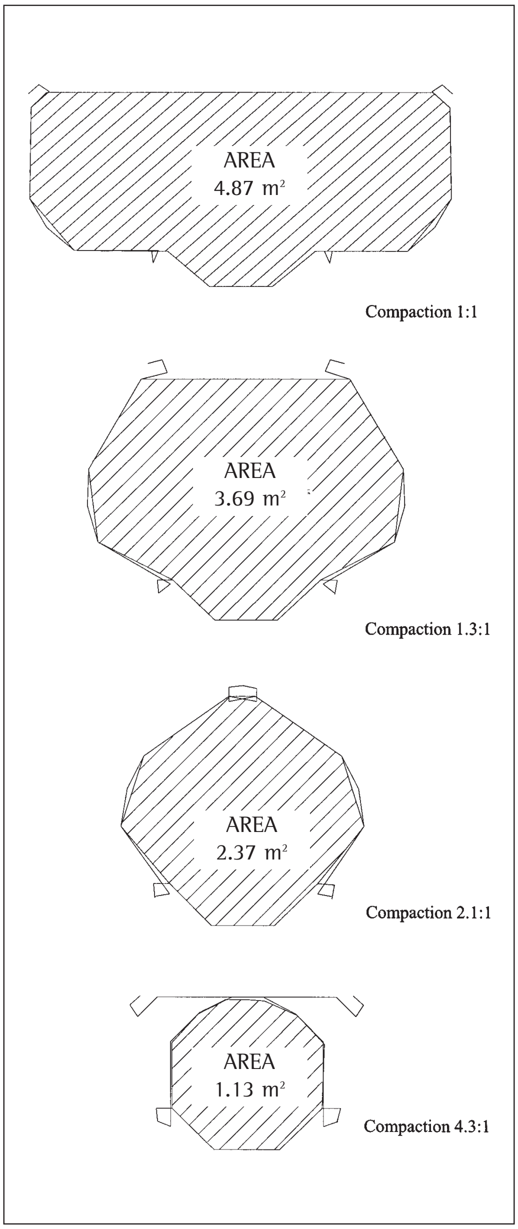

Figure 8: *Compaction of residues using folding framework.*

pre-compacted during the filling of the bundler. Nevertheless the initial load was taken to have a unit relative density. An indication of the final packing density is given in Section 6.3.

6.1.4 Hydraulic System

The motive power for the compaction process came from four hydraulic cylinders arranged at the corners of the machine. The base frame and the wing frames were designed to be able to withstand stresses approximately four times higher than those which the hydraulic cylinders could create. The facility to add a further two hydraulic cylinders at the centre of the machine was incorporated in the design scheme. One of the versatile features of the prototype comes from the ability to use hydraulic pressure from a tractor, forwarder or independent power pack. The cylinders were specified to work at up to 200 bar (3000 psi) but in practice some forwarders are not able to provide pressure above 130 bar (2000 psi). The cylinders were inverted and trunnion-mounted to make them more compact and to maximise the force at the closed position. This introduced problems with hoses which were subject to damage in service.

For further development of the bundler, relocation of the cylinders and an alternative to the flat base, in order to fit the bundler to specific forwarders, should be addressed. This should enable the bundler to be lowered by as much as 400 mm, thereby improving stability and making loading easier.

6.1.5 End trimming

The issue of how to deal with the ends of the bundles was not resolved and the bundle ends were left untrimmed and unconstrained in the first prototype. However, a number of potential mechanisms were considered. Moving baffles might push the bundle ends into place as the radial compaction occurred, but it was not known how the material would move axially. Material exceeding 2.4 m might need cutting or breaking to make it fit to the bundle dimensions.

6.1.6 Strapping

Two design studies were undertaken to examine bundle end containment and strapping. While a number of options were carefully considered during the design of the main structure it was decided to use manual strapping for the prototype testing phase. Pneumatically operated crimper/tensioners, used for banding log bundles for shipping, were used. The strapping was 2 x 30 mm steel banding, joined using overlapping crimps (Figure 9).

6.2 Machine build

The relative simplicity of the final design belied difficulties in its analysis. The structure was complex in three dimensions and caused some concern in relation to its rigidity. However, once the detailed design was completed successfully, it was a relatively easy task to fabricate the components from sheet steel and rectangular hollow sections. The structure was partially fabricated at the University of Limerick workshops using parts made both at the University, and at the premises of the other partners in the project Keltec Limited (Co Limerick) and Teva Limited (Co Galway).

Figure 9: *Strap joined by crimps (centre) with good material orientation in the bundle.*

6.3 Machine operation

6.3.1 Bundle manufacture

The procedure was as follows:

1. the frame arms were opened and the logging crane/grapple was used to fill the cavity with residues. (The operator tried to orientate the residues parallel to the cross axis of the machine. Care was taken to fill the machine relatively evenly across its full width. During filling, the operator would occasionally compress the load vertically with the grapple, to settle it into place.);

2. once the machine was full of residues, level with the tops of the framework, the crane was stowed across the top of the load to provide stability for travelling. (In fact, it was unlikely that the load would have been lost as it sat quite firmly in place.);

3. the machine travelled to the road head where the crane was lifted and swung clear, the frame was closed using power from the tractor hydraulics - it took about three minutes to fully close but could have been made quicker by revving the

tractor engine at a greater speed. (Hydraulic pressure readings were taken as the closure occurred so that the forces and energy required for compaction were measured.);

4. when the bundle was fully formed the strapping was manually fitted at two points around the bundle, about 2 m apart;

5. the arms were opened and the bundle was removed, weighed and stacked.

The average cycle time to produce a bundle varied between 0.5 - 0.75 hr depending on the extraction distance.

6.3.2 Varying bundle size and compaction ratio

The bundler was designed in such a way that additional components could be fitted to make a smaller bundle if required. Once in the field, it was found that the bundle size could be varied to some extent without these additions. To make a larger bundle, the machine was overfilled and as there was not sufficient force for the machine to be completely closed, the bundle had a larger diameter. It was still possible to strap the bundle adequately but the increased diameter was very difficult to grasp. Smaller bundles were made by only partially filling the machine and using the strapping tensioner to get a good reduction in diameter. This was not very successful, as the bundle tended to be loose and hence easily damaged. The cycle times varied very little (0.50-0.75 hr) so the heavier the bundle the greater the productivity.

As indicated in Section 6.1.3, the compaction ratio was estimated to be approximately 3:1. This represented the geometrical ratio available in the machine and the force of the hydraulics was adequate for this. It was possible to vary this ratio by increasing the load by 'pre-compacting'. This entailed closing one or both moving side frames to partially compact the bundle and then opening them again and filling in more material. Under these conditions it was found that the amount by which the material would spring-back was only 50%. This enabled more material to be introduced into the gaps created at the front and back of the cavity. In practice only the rear frame was operated (Figure 10) and the gap created at the back was filled. Using this method compaction ratios of up to 6:1 were achievable.

6.3.3 Bundling trials

Bundles were made at three sites. Test sites were selected with a variety of residue material and site conditions. The first site was used for commissioning the bundler. Seventy-nine bundles were produced throughout the commissioning and trial stages – three at Cratloe, seventy at Murroe and six green bundles at the Buffanoka site.

6.3.3.1 Site 1 - Commissioning

The site for the commissioning trials was at Cratloe, Co Clare. The trials at Cratloe produced three bundles which remained intact for more than six months. The first bundle was made on a steep site covered with residues from windthrown trees, including broadleaves and conifers. Two further bundles were made and strapped on a more suitable terrain using a mixture of residues from Sitka spruce and lodgepole pine. A number of small structural and hydraulic problems identified during commissioning were solved.

6.3.3.2 Site 2 - First trial site

The first field trial site proper was at Murroe, Co Limerick. The forest residues had been windrowed

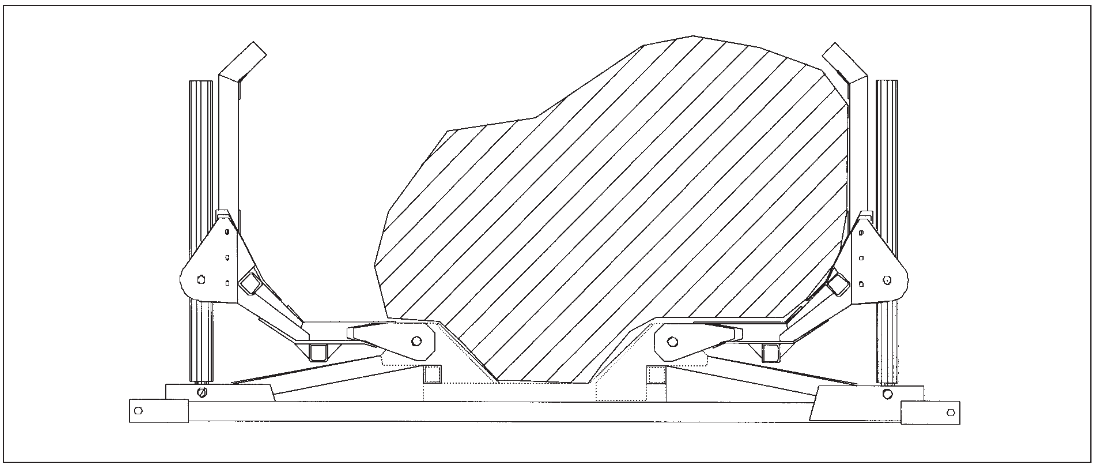

Figure 10: *Partial compaction of residues to one side of frame to make room for additional material to be added.*

***Figure 11:** The prototype Limerick bundler working with windrowed residues at Murroe, Co Limerick.*

***Figure 12:** The bundler working at Buffanoka loading (fresh) green residues from a brash mat.*

by an excavator into substantial, longitudinal rows (Figure 11). The residues were generally tangled and contaminated with soil (and some quite large stones). The random orientation and the length of some of the material (over 7 m) gave the row a very low density. This facilitated natural drying during the summer months. The very dry nature {approximately 50% m.c. dry basis (d.b.)} of the Murroe material was helpful in making the bundles easier to off-load and stack. However, the tangled nature of the residues made for very slow production rates.

6.3.3.3 Site 3 - Second trial site, Buffanoka

After the Murroe site the bundler was moved to a close-by, clearfell site at Buffanoka (Figure 12). The soil had a peaty top horizon, about 600 mm deep, over a stony subsoil. The roundwood had been extracted by forwarder, which had travelled over brash mats. This suited the project requirements as one of the objectives was to examine handling and bundling of both fresh (recently felled) green material and brash mats. The mats were well compacted by the fully-laden forwarder – in fact much of the residue material forming the mats had been pushed well into the soil. Without a brash mat the forwarder would have had great difficulty in traversing the site, and payloads would have been reduced greatly. Overall the site proved to be very difficult for the forwarders hauling roundwood and residues. It highlighted the need for an improved machine that could traverse such sites. The site proved to be impossible for the bundler after a change in the weather made conditions even more slippery to the point where it became dangerous to traverse.

7. HANDLING, HAULAGE, STORAGE AND ANALYSIS OF BUNDLES

7.1 Handling and haulage

The bundles were handled frequently during manufacture and stacking, and while being measured (Table 1). The machinery used for handling included a forwarder (unloading, stacking and weighing), a loader (stacking and loading on truck) and truck crane (unloading and stacking). Most bundles were handled 12 times (Table 1) but some were handled more frequently due to being stacked vertically or re-arranged on the stack.

The bundles were hauled using conventional forestry trucks (Figure 3).

7.2 Determination of bundle weight

Each bundle was weighed at a number of stages using a customised loadcell. The loadcell was attached to two slings which were hooked into the straps of the bundle, which was then lifted and weighed (Figure 13).

Table 1: *Bundle handling operations and methods.*

OPERATION	METHOD
Unloaded from the bundler	Forwarder grapple
Lifted and weighed by load cell and straps	Suspended from straps
Lifted into a stack at landing	Forwarder grapple
Lifted to position for re-weighing (some time later)	Loader
Trimmed and lifted back to the stack	Loader
Loaded to the truck	Truck crane grapple
Unloaded from truck	Truck crane grapple
Lifted into the stack	Truck crane grapple
Re-weighed	Suspended from straps
Lifted from stack	Grapple
Re-weighed	Suspended from straps
Re-stacked/uprighted	Grapple

Figure 13: *Bundle being weighed using customised loadcell.*

7.3 Trimming

As noted in Section 6.1.5 the bundler had no facility to trim the bundle ends. As the residue material varied considerably in length the ends tended to be very scraggy. In order to facilitate storage the bundle ends were trimmed using a chainsaw (Figure 14). This operation took place at the end of Storage Period 1 (Section 7.4.1). It was quite time consuming due to the need to weigh the bundles both before and after cutting. A number of chainsaws were tried. These varied from conventional fuel powered saws to a prototype hydraulic chainsaw.

7.4 Storage

7.4.1 Storage Period 1 (August 1996 - December 1996)

The bundles were first stored at the Murroe site from August to December. The rainfall during this period was approximately 90 mm/month, daylight averaged 12 hours. The bundles were stacked horizontally in groups, with three on the bottom and two on top (Figure 15).

Figure 14: *A trimmed bundle with trimmed material piled to left-hand side.*

Figure 15: *Untrimmed bundles stored in a large stack from August to December 1996.*

7.4.2 Storage Period 2 (December 1996 - April 1997)

Some thought was given to stack configuration for commercial storage (horizontal v vertical) of bundles. To investigate stability, two stacks were built in a horizontal and vertical orientation respectively, and left for one week.

After the initial weathering and trimming, some of the bundles were brought to the University of Limerick for closer examination. Others were taken to Finsa Limited at Scarriff, Co Clare where the effect of bundle orientation on drying was examined by stacking vertically and horizontally (Figure 16). It was expected that the vertically stacked bundles would dry faster as there was less surface area exposed to rainfall and more exposed to the wind. The separation between rows varied from 300 to 500 mm, to facilitate air movement.

7.5 Analysis of bundle/residue material properties

One bundle was selected and dissected to give some indication of the properties of the residue material.

The procedure for sampling the bundle was as follows:

- approximately a third of the way along the bundle (between the strap and the centre of the bundle), a 150 mm wide slice of maerial was removed;
- 25 sample points were marked on the end face of the bundle;
- 50 g samples of wood and needles were taken at each point and sealed in bags, to determine moisture content;
- a further cut was made through the bundle approximately 150 - 200 mm from the first;
- all of the material between the first and second cut was sorted by diameter into bags for analysis of material size.

The following properties were determined:

- *material size:* the branch material was trimmed as it was sorted, all of the material was carefully collected and sorted by diameter into bags;
- *moisture content:* the 25 samples taken were oven dried to determine moisture content. Each sample bag was opened and divided into eight parts, four of these being woody material and four being fines (<5 mm diameter). Three of the small and three of the woody samples were then dried according to standard procedures. One was retained as a representative sample.
- *calorific value:* an analysis of the calorific value, on a dry ash free (d.a.f) basis, of the dried samples was carried out using a bomb calorimeter according to ASTM D4442-92, ASTM E711-87 and BS1016 Part 5.

Figure 16: *Stacking arrangements of bundles.*

8. RESULTS

8.1 Bundle weight change during storage, trimming and stacking

8.1.1 Storage

The original bundle weights ranged from 500 to 1200 kg with a mean of 893 kg. Following the initial storage period the weights ranged from 660 to 1544 kg, the mean had increased to 1069 kg. Hence, the mean weight gain was 176 kg, or the equivalent of a 20% increase over the original mean bundle weight. The mean bundle weight following the second storage period from December to April was 636 kg (range 250 - 1100 kg). The mean weight loss was 261 kg, which represents a loss of 30% of the December trimmed bundle weight. Only one bundle gained weight while five lost more than half their weight.

8.1.2 Trimming

When the bundles were trimmed in December 1996 they were re-weighed to determine the quantity of material that was removed by trimming. The mean quantity of material removed was 170 kg, or 20% of the final trimmed bundle weight, at the end of the initial storage period. The trimmed bundle weights ranged from 620 to 1286 kg with a mean of 891 kg.

8.1.3 Stacking

An attempt was made to have an equal distribution of bundle weights between the horizontal and vertical groups. In practice the vertical group was formed using lighter bundles, mean weight 826 kg in December, compared to a mean weight of 927 kg in the horizontal group in December (Table 2). Expressing the April 1997 weight as a percentage of the December 1996 weight, the means were 66% and 78% for the vertically and horizontally stacked bundles respectively.

8.2 Bundle and bundle stack stability

About 10% of the bundles disintegrated as a result of handling, but these were visibly poorly formed bundles. Stacks which were comprised of two rows of horizontally oriented bundles were quite stable while the two rows of vertically oriented bundles were very unstable (Figure 15).

8.3 Bundle/residue material properties

Section 7.5 outlined how bundles were analysed to determine the range of material sizes. As Table 3 illustrates, over half the material from the sectioned bundle was less than 5 mm diameter, and can be classed as fines. The fines consisted mainly of needles and small twigs. Only a quarter of the material was greater than 15 mm diameter (Table 3).

Table 3: *Particle size distribution (by dry weight) of residues (data from one bundle only)*

Diameter mm	Weight kg	Proportion %
<5	79	63
5-15	12	9
16-30	19	15
31-60	8	6
60	9	7

8.4 Bundle moisture content

The mean moisture content for the larger material and fines were 50% (w.b.) and 70% (w.b.) with ranges of 33-74% and 47-78% respectively.

8.5 Calorific Value

The gross calorific value of the samples was calculated on a dry ash free (d.a.f.) basis, as illustrated in Table 4.

Table 4: *Calorific value of bundle components (data from one bundle only).*

Component	Gross Calorific Value MJ/kg (d.a.f.)
Solid material	20.5
Needles & fines	21.5
Bark	22.5
Solid material with 30% m.c. (d.b.)	10.5

Table 2: *Comparison of weight loss of horizontally and vertically stacked residue bundles.*

Stacking orientation	Date	Minimum weight	Maximum weight	Mean weight	Mean weight loss
		kg			%
Horizontal	December	650	1286	927	-
	April	250	1100	733	21
Vertical	December	555	1234	826	-
	April	310	875	554	34

9. DISCUSSION

9.1 Machine operation

The bundler and forwarder operated without any major problems during the trials. Indeed, the majority of difficulties were caused because the bundler was originally designed to be a landing based machine and was modified at a late stage in the design process to be attached to the forwarder. This meant that there were some problems with stability, the crane position and hydraulic systems.

As Figure 17 illustrates, there was a large gap between the bundler base and the wheels of the forwarder trailer. This raised the centre of gravity of the machine and the operator found that the machine had less stability compared to when it was utilised to extract logs. The bundler base would need to be re-designed to allow for more successful integration with the forwarder.

The operator also had some problems loading the bundler because the crane boom was slightly lower than a normal forwarder crane boom. It was also positioned too close to the bundler. As a result the operator found it difficult to fill the front of the bundler and this affected productivity (Figure 18).

Figure 18: *Boom of crane was too close to rams of bundler.*

Another factor affecting the operation of the machine was the specification of the forwarder's hydraulic system. It was not adequate to operate the bundler as quickly as was expected. Again, re-design and correct integration with the forwarder would reduce or eliminate this problem.

Figure 17: *The bundler compacting some fresh green spruce (note the base of the bundler is well above the tyres.*

As expected, the strapping process presented some problems as it was carried out manually and the pneumatic equipment was rather unwieldy. However, considerable experience was gained on strap positioning and movement as the bundler arms closed. Progress has been ongoing in an attempt to develop alternative strapping systems which can be semi-automated and which use straps that are recyclable and/or re-usable.

9.2 Production of bundles and performance of bundler on different sites

In terms of first effort, the Cratloe trials were successful in that residues were bundled at the first attempt. They were 1.6 m diameter, cylindrical and 3 m long and contained over 1 t of material. Considering how dry the material was, (approx. 50% m.c., d.b.), this represented more material than anticipated. The bundle ends were however, very scraggy and no method of solving this problem had been developed to date.

The work at Murroe was more demanding as the site was sloping and very wet in the middle where the main extraction route was located. The large number of substantial timber lengths slowed progress as each had to be cut or broken. Manual cutting of the pieces of wood was not possible in most cases because of their position within the windrow. Also, to facilitate the experimental work, the forwarder was bringing each load out to the landing for strapping and weighing. Thus, over half the cycle time (and in some cases two thirds) was wasted travelling unnecessarily over the site. The preferred mode of operation would have been to make the bundle alongside the windrow, strap and unload it for later collection by a modified forwarder capable of carrying up to six bundles at a time.

The trials at Buffanoka were disappointing. It rained heavily shortly after the machine arrived on-site and this added to the problems of dealing with a peaty soil. An experimental ‘fixed side’ had been fitted to the machine to attempt to produce bundles with one flat end. The additional weight proved too much for the ground to support. Furthermore it shifted the centre of gravity of the machine, making it unstable. The forwarder had, of necessity, to travel off the brash mat in order to harvest it and this proved to be very difficult. Uphill progress was almost impossible, even with chains on the tyres, and downhill travel was dangerous as the site became progressively steeper, culminating in a drop, as it approached the forest road. About 10% of trees had been manually felled at the site, as they were too large to be felled by machine. The resulting stumps were quiet high, and this restricted forwarder travel. Deep plough furrows also contributed to the difficulty of traversing the site. However, the design team gained valuable experience about the needs of a forwarder on such terrain and, in the circumstances, a lot of lessons were learned. It was primarily on safety grounds that work stopped at the site.

Overall at the two sites productivity was very variable. Generally only about ten bundles were made and delivered to the road-head per day. Considering the nature of the material and the extraction conditions, an improvement in productivity to 40-50 bundles per day could be expected following improvements to the strapping mechanism. Furthermore, an initial assessment of the productivity and economic feasibility of a number of forest residue bundling systems carried out by Hoyne (1996) showed that one system where bundles are extracted one at a time to roadside was one of the most unproductive of all the systems he analysed. A system (op. cit.) that unloads the bundles as they are produced - to be extracted later using a modified forwarder carrying up to six bundles - should be the most economic and productive terrain bundling system. Further work would be required to support this study with field data.

9.3 Bundle manufacture

The bundles had diameters ranging from 1.2 to 1.6 m with a mean weight of approximately 900 kg (Section 8.1). In practice, a compaction ratio of 4:1 was achieved and the hydraulic force was adequate to achieve this.

As noted in Section 6.3.2, the bundle compaction ratio was varied by pre-compacting the material by closing and opening the frame, to partially compact the material, and then loading more material into the gaps left in the front and back. This method met with a varying degree of success. As noted, the grapple/crane of the forwarder was too close to the front of the bundler, having been designed to load logs at the middle of the machine, and therefore it could not reach fully to the front to fill the gap created. Operating just the rear frame and then filling the gap at the back solved this problem. However, this introduced a second problem as the operator, not having very good visibility, could introduce too much material, the equivalent to a 6:1 compaction ratio, and the hydraulic rams were not able to provide sufficient force to fully close the frames. Thus, it is estimated that the best compaction achieved was of the order of 5:1, using a two-phase compacting cycle.

9.4 Trimming of bundles

Although the bundles had relatively consistent diameters and were cylindrical in shape the ends were uneven and scraggy. The attempt, at the Buffanoka site, as described, to produce bundles with one flat end, was unsuccessful, and the bundles were trimmed manually. The trimming operation was carried out at the end of the initial storage period in December 1996 and as described, a number of chainsaws were used to trim the bundles. However, it was found that the trimming operation was hazardous. The chains suffered wear as some of the inner material tended to move about and because the residues contained soil and stones.

The most successful saw used was a prototype hydraulic chainsaw. It was successful at cutting but lacked the safety features normally associated with petrol saws. It was fitted with a coarse pitch chain of very good quality material, which needed less sharpening than conventional saws. The work demonstrated that chainsaws could be used for end-trimming of the bundles but they would need development and would need to be placed on the machine and properly housed to prevent accidental damage.

There is some merit in considering the option of leaving the ends untrimmed but this would only be in cases where the bundles were to be used locally. As soon as road or rail transport is required, it is essential to trim the bundles to increase density (the scraggy ends are bulky) and reduce lengths to legal limits. Future generations of the bundler could be fitted with an end-trimming device.

Figure 19 illustrates a proposed option for fitting end-trim saws. This arrangement will be a difficult development task and support for the end of the chain bar and a waste stripper will be required.

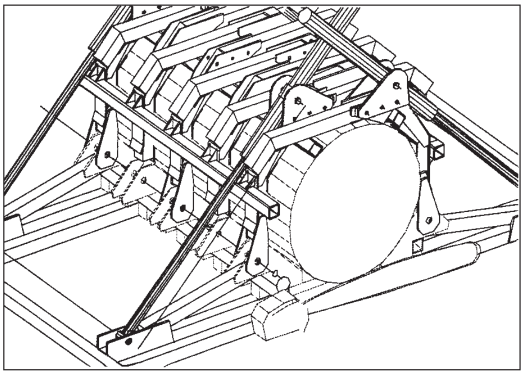

Figure 19: *Proposed option for end trimming.*

9.5 Needle loss from bundles

One of the objectives of the project was to examine dry matter losses from the bundles. At the outset, it was considered that loss of needles would be a waste of potential fuel but this later changed as the analysis of the material properties (Sections 8.3-8.4) showed that while they were of equivalent dry matter calorific value, the moisture content was considerably higher. Furthermore, site productivity could be reduced by excessive removal of needles due to their high nutrient content. It was concluded that a device, which causes needle shed at the de-limbing stage would be desirable, or the residues could be placed in piles and left to dry to encourage needle fall. In general, it was felt that if 50-75% (dry matter) of the residues were removed post harvest and most of the needles were left behind, it would satisfy the needs to maintain site productivity and have an economic volume of residues to harvest. Recovery of more than 75% of the residues would be increasingly unproductive. This was observed at the Murroe site where it was fully cleared for a woodland park development. Gathering the remaining material was very time consuming.

It was too difficult to make an accurate assessment of needle losses due to limited resources. However, an estimate was made based on needles collected from four sample areas and observation of the harvested material. At the Murroe site, the material had been lying for some months and was well seasoned by the dry spring weather. There was a substantial (>80 mm) needle cover on the forest floor but it was not clear how much of this had fallen since harvesting. Analysis of the residue material during harvest suggested that at least half of the needles had already been lost from the branches. Nonetheless, this site was windrowed a few months after felling and this disturbance would have resulted in the shedding of some needles. There was clear evidence from the accumulations on cut stumps near and in the windrows that some needles had been shed during harvesting. The Buffanoka site was totally different in that the residues were in brash mats. There was little evidence of needle loss from the residues but it was clear that there were large needle accumulations on the forest floor. Needle retention/loss needs to more fully examined and should be a priority area in further research.

If forest residue harvesting is to develop commercially it will be essential to establish integrated harvesting techniques and systems. Such systems can produce alternate piles of residues, separated from brash mats, which can be allowed to dry and harvested with more ease. As stated, residues should preferably be left on site for a period of time, following the roundwood harvest to facilitate needle shedding.

9.6 Handling and haulage of bundles

Only 10% of the bundles produced disintegrated (Section 8.2) during handling and these were badly made bundles. Most damage occurred during the trimming process. The handling of the bundles was done by means of an articulated industrial loader, fitted with a silage fork.

When lifted out of the bundling machine with the logging grapple the bundles handled well. There was some difficulty retaining a grip on the bundle, as the grapple was a common forwarder grapple specifically designed for logs. The ends of the tines were joined by a flat plate which made penetration into the bundle difficult. This highlighted the need to use a specialised forest residue grapple (Figure 20) which would be better suited to handling bundles and loose residues.

Figure 20: *Forest residue grapple.*

The opinion of all the operatives concerned was that the bundle size and weight were about right for the available machines. If a higher compaction ratio could be achieved then there is a case for making the bundle a little smaller so that the average crane could handle it. Certainly, a weight of over 1.5 t would cause some difficulties on sloping sites without stabilisers on the crane.

9.7 Bundle drying

9.7.1 Weight loss over time

The material from the Murroe site was so dry (<50% m.c., d.b.) at the time of harvesting that there was little or no scope for further drying. In fact, the unusually dry summer and the well seasoned nature of the material, presented a major problem. This factor suggested that it would first be necessary to increase the moisture content of the bundles before the drying rates could be studied. It was thus decided to leave the bundles in stacks at the Murroe site from August to December so they would be exposed to the weather during autumn and most of the winter. Surprisingly, a small number of these bundles lost weight during autumn but most gained weight. There is, of course, a low drying potential in Ireland during the period September-November. Consequently, weight gains were substantial. On average, bundles gained 20 % with the mean bundle weight increasing from 893 to 1069 kg (Section 8.1). It is reasonable to assume that this was attributable to moisture gain. Some bundles may have gained more weight due to their position in the stack and the proportion of needles that they contained. It was not an objective of this study to assess how bundle weights were affected by the position of the bundle in the stack. However, further studies are needed to assess this in detail in an attempt to determine the optimum stack size.

As the bundles had gained weight from exposure to the elements during the initial storage period it was expected that there would be a degree of drying during the December to April period. This was indeed the case with all but one of the bundles losing weight. It can be seen (Figure 21) that there was no obvious pattern relating weight loss to the original weight of the bundle - one of the heaviest and one of the lightest each lost over half their weight. They were stored in such a way that each bundle had similar air circulation and incident rainfall. It was already known that there was a large range of moisture content between the bundles placed at Finsa and that it was possible that some of the heavier bundles were very wet. It was not possible to measure the mean moisture content of every bundle within the group. The mean bundle weight at the end of the period was 636 kg (Section 8.1) which represented a 30% weight loss from the trimmed bundles weighed in December.

The fact that the bundles were able to dry to below the trimmed mean bundle weight over the second storage period was particularly encouraging. This would seem to indicate that forest residues with a relatively high moisture content could be bundled and the bundles will dry under the right weather conditions. Also, the condition of the bundled, dry material did not seem to deteriorate dramatically during the eight months that they were stored.

It is recommended that sites from which residues are to be harvested would be felled a number of months prior to bundling. This would allow for moisture and needle loss before the residues are bundled. The

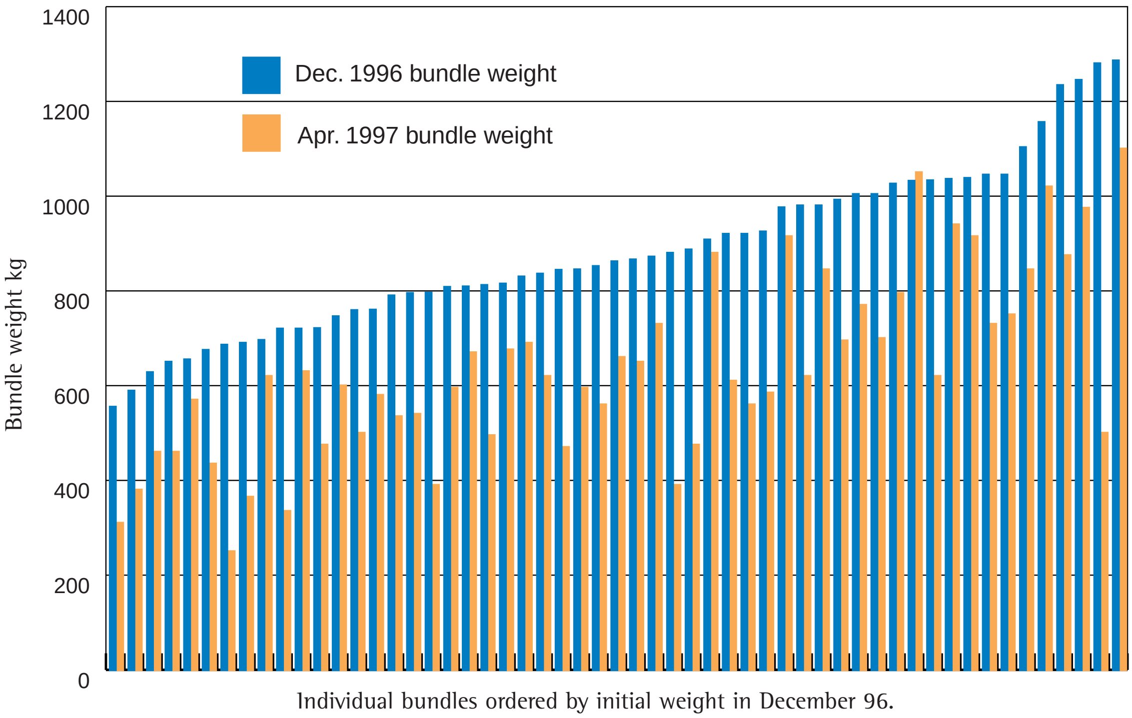

Figure 21: *A comparison of bundle weights following exposed storage at Finsa from December 96 to early April 97.*

bundled material could be stored in the knowledge that any weight gain due to exposure will be lost if the bundles are stored over a spring or summer period. With the correct harvesting regimes and scheduling it should be possible to produce bundled material with a reasonably low moisture content throughout the year.

9.7.2 Drying and bundle orientation

In addition to examining whether the bundles would dry after gaining weight over the winter period, an assessment was made as to whether weight loss was affected by stacking bundles in a horizontal or vertical position. Clearly, the upright bundles would be exposed to less rainfall due to the smaller vertically projected area and likewise, they would have been more exposed to air circulation.

The initial assessment of the data seems to indicate that the vertically oriented bundles apparently lost much more moisture, hence confirming the hypothesis. However, closer examination reveals some discrepancies. The intention was to divide the bundles in December 1996 in such a way that the mean weight of the horizontal and vertical groups was approximately equal. However, this did not occur; the haulier had shown a preference for putting lighter bundles on end, apparently due to limitations with the truck crane lifting capacity. The December 1996 bundle weights confirm this bias, with the mean horizontally stacked bundle weight being 927 kg compared to 826 kg for the vertically stacked group. This error in the distribution of bundles means that the comparison of the drying behaviour of horizontal versus vertical groups is not entirely conclusive. The reason for a number of the bundles being lighter is probably due to a number of factors. First, as mentioned earlier, there were some variations in bundle size and compaction ratios. The smaller bundles produced with lower ratios would obviously be lighter. Also, the lighter bundles may have been made up mainly of larger, drier, solid material containing small amounts of needles and other small-sized material. These bundles would have absorbed less water during the initial storage period and hence be lighter. Finally, another factor influencing the trimmed December 1996 weight would have been the position of the bundle in the stack at Murroe, with bundles in the centre of the stack being less exposed to rainfall that those positioned on the top of the pile.

A smaller sample of eight bundles from each of the horizontally and vertically stacked groups, with approximately equal mean December 1997 weights, was taken in an attempt to provide a more conclusive analysis. The December 1996 weight of the sub-set of bundles selected ranged from 700 to 1050 kg and the mean December 1996 weight of each group was approximately equal (873 kg horizontal, 880 kg vertical). However, when the mean April 1997 weights are assessed there is a considerable difference with the horizontal and vertical means being 661 kg and 569 kg, respectively. Expressing the April 1997 weight as a percentage of the December 1996 weight results in the horizontal mean being 75% and a vertical mean of 66%. It would seem reasonable, therefore, to conclude that bundles stored vertically are likely to dry more rapidly and to a lower final moisture content than those stored horizontally under otherwise similar conditions. However, these data must be treated with caution. It would be necessary to carry out further storage trials where the horizontally and vertically stacked groups are made as similar as possible. Indeed, in future studies it would be advisable to ensure that the bundles be made of relatively similar material, produced with the same compaction ratio and stored under identical weather conditions. From a practical point of view the bundles were stable when stored in the vertical position.

9.8 Residue size distribution and its effect on conversion

End-trimming of the bundles revealed the variation in the size of the residue material in the bundles. Some bundles had large amounts of needles and small material whilst others were made up of larger, woodier material. The bundle that was examined had over 60% of its mass in small material and was, in hindsight, unrepresentative. The moisture content of the small material was much higher and it represented less than 40% of the dry matter in the bundle. The moisture content of the samples from this bundle emphasised the need to reduce the percentage of needles and fines as their moisture content was, on average, 20% higher than that of the solid material. This high moisture content presents a number of problems. The process, be it combustion or gasification, whereby the residue material is converted to energy will be affected by the moisture content of the feed stock. Generally, the acceptable moisture content ranges for plants of 0-1 MWth and 1-5 MWth are 25-40% (w.b.) and 40-55 % (w.b.), respectively (Alexander 1994). It would be important therefore, to reduce the amount of needles in bundles by leaving the residues to dry on site and needle shed to take place. Furthermore, combustion and gasification processes are also negatively affected by a high percentage of fines in the feedstock as the ash and silicon content increases in proportion. The size of the larger solid material will depend on the top-diameter at which the trees are cross-cut and on whether there are significant levels of waste and dead wood on the site.

9.9 Bundle appearance, fungal growth and self-heating

The bundles which were stored at Finsa were examined after eight months exposure to autumn, winter and spring weather. During the autumn and winter months there was substantial weight gain due to rain but there was considerable drying during spring. However, there had been no visible deterioration of the bundles due to weathering. The green bundles showed substantial signs of browning and some needle loss from the outer branches.

It has been observed that wood chips which have a moisture content below 25% (d. b.) are not subject to deterioration due to fungal attack (O'Donnell 1993). Above this level there tends to be temperature increases due to respiration caused by bacteria and fungi growing in the material. A higher percentage of fines will present a greater surface area for bacterial and fungal activity, therefore increasing the potential for deterioration of the material

The bundle which was examined (Section 7.5) contained a great deal of needles and small material. Visual inspection of the material showed considerable blackening of the needle material but no obvious deterioration of the larger wood pieces. Smell is often an indication of fungal growth and in this case there was no unpleasant odour. Fungal growth may have been still in the early stages of development.

9.10 Calorific value of the bundled residues

The calculated gross calorific value (GCV) compares well with values given in literature for conifer residues. Alexander (1994) gives a value of 20.90 MJ/kg (d. a .f.). The GCV represents the effective heating value of the material plus the latent heat of water required to be evaporated in the combustion process. This value and the moisture content are used to derive the Net Calorific Value (NCV), or effective heating value. There are a number of equations available for doing this but the one developed by Mitchell et al. (1990) was used:

Net CV (GJ/gt) = GCV (d. b.) - (factor x % moisture content) 1

Extensive trials carried out during the Mitchell et al. (op.cit.) study developed equations for three different fuel types assuming that the percentage of ash and hydrogen were 1% and 60%, respectively.

The equation for conifer residues was:

Net CV (GJ/gt) = 19.46733 - (0.2197 x % m. c.) 2

This equation was used to determine the NCV for the solid material and fines in the sample bundle (Table 5).

Table 5: *Net calorific value determined for solid and fine material samples of dissected bundle.*

Parameter	Solid material	Fines
Moisture content (w.b.) %	50	70
Moisture content (d.b.) %	25	1.5
Gross Calorific Value (d.a.f.) MJ/kg	20.5	21.5
Net Calorific Value MJ/kg	14	11.8

The calculated figure for the solid material compares well with the value for wood quoted by Landen (1993). As expected the NCV for the fines is considerably lower; this further emphasises the need to reduce the needle content of bundles.

The total gross and net calorific value of the bundle was also determined knowing the quantity of the dry matter in the bundle. On the basis of the volumetric measurements, sample measurements and moisture content it was estimated that the amount of dry matter in the sample bundle was 0.43 t. From the above data the total GCV and NCV of a perfectly dry bundle would be of the order of 9 GJ and 6 GJ respectively. This suggests that one bundle of residues has an equivalent thermal value of 140 kg of gas oil. However, the latter fuel burns more efficiently and the oil equivalent of a bundle will be rather lower than 140 kg.


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10. CONCLUSIONS

The work represented a significant contribution to the experience base and sufficient data have been collected to enable the design of a commercial, first-generation machine. The compaction of forest residues is also being developed in Sweden and a refuse baler has been adapted for the production of bales of forest residues (Hoyne 1996). However, this Bala baler has a very high capital cost and may not have the flexibility to handle a variety of materials. A commercial bundler could be produced at a fraction of the Bala baler cost and could be considerably more versatile.

Some first steps were made to determine the potential markets for forest residues as a fuel while the bundles were being stored at the Finsa Ltd. plant. The latter has a large energy demand for chipboard manufacture and an associated combustion plant. The company normally uses oil as a primary fuel though waste wood and bark are also used. Residue bundles have considerable potential as a fuel source in such plants. Similar plants could be identified as potential users of residues.

Many large bundles were made, stored and transported with success. The bundling machine functioned well and gave an indication of the kind of problems likely to arise in developing a commercial version. Experience was gained in strapping materials and some of the difficulties of automating the strapping process were identified. It was estimated that less than 1.0 MJ of energy was consumed to compact each bundle. This work has continued, and the bundles are in open-air storage in stacks, and are being subjected to further weathering.

Further stages of development could include:

- design and build cut-off saws for the bundle ends;
- add two further rams to achieve higher compaction densities;
- operation on a forwarder more suited to the bundler;
- design of a forwarder rear half integrated with a bundler;
- further development of strapping techniques;
- experiments with higher compaction densities and smaller diameter bundles (1.0 m);
- a more detailed study of drying rates and moisture distributions;
- a forced air drying study;
- bundling of coppice material from short rotation forestry.

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