

**Drying of willow biomass
in supply chains**

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Drying of willow biomass in supply chains

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Abstract

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Keywords: logistics; supply strategies; optimization; short rotation coppice; wood; diffusion model; forced convective drying; natural wind drying

The drying process of willow (*Salix viminalis*) in biomass supply chains to energy plants is quantitatively described. Drying at particle level was modelled for chips and stems by a diffusion equation linked to the mass transfer of moisture to the air. Drying at bulk level is described by a deep bed model, which accounted for the moisture and temperature gradients of wood and air therein. Experimental validation showed that the deep bed model adequately described forced convective drying (with ambient air) of a willow chip bed, and natural wind drying of willow stems in large piles. The technical possibilities and costs of drying of chips, using farm facilities for potatoes, were assessed. March to September turned out to be the most suitable period. Compared to harvest costs, forced convective drying was a considerable cost factor. For stems, statistical analysis of experimental data showed that a pile dried uniformly, except for the top layer. Pile coverage had no long term effect on the moisture content. Within a single stem, the moisture content was largely uniform. During open storage from harvest (December-April) until August, the moisture content could be reduced to close to that of the equilibrium moisture content. Experiments and model calculations showed that chunks could be dried relatively quickly by forced convective drying, and very cheaply by natural wind drying. A model was developed to optimize supply chains by Dynamic Programming, which proved to be useful in deriving supply strategies. The natural wind drying time, required to achieve the correct moisture content, specified by the energy plant for chunks and stems, was a decisive factor in the design of supply chains.

Stellingen

1. Een wilgenstengel met bast gedraagt zich als een geroerd vat met een vochtdoorlatende wand.
Dit proefschrift.
2. Bij chunks (blokjes) bepaalt de diepte van de stapel de gewenste droogtijd.
Dit proefschrift.
3. Een wilgenstengel heeft geen last van stapelen.
Dit proefschrift.
4. Vaststelling van de prijs van biomassa op netto calorische basis, in plaats van het gangbare systeem (op basis van drogestof), biedt voordelen voor zowel de brandstofleverancier als de energiecentrale.
5. Vergelijking van logistieke ketens met verschillende begin- en/of eindcondities, zoals onder andere gedaan door Mitchell et al. (1995), Allen et al. (1997) en Sims and Culshaw (1997), is zinloos.
Referenties opgenomen in proefschrift.
6. *Fitparameters* van droogmodellen moeten met een hoge nauwkeurigheid worden bepaald, hetgeen echter geen garantie is voor de juistheid van deze parameters.
7. Verrijkte voeding verrijkt het leven op latere leeftijd.
R.P.J. van der Wielen, 1995. Vitamin intake and status in elderly Europeans. PhD-thesis, Wageningen Agricultural University; N. de Jong, 1999. Sensible Aging – Nutrient dense foods and physical exercise for the vulnerable elderly. PhD-thesis, Wageningen University.
8. Het gevaar van 'Joint Implementation' is vluchtgedrag.
'Joint Implementation' betekent dat milieuwinst, behaald met Nederlandse investeringen in duurzame energie in het buitenland, (gedesettelijk) meetelt in Nederland.
9. Het is niet de bedoeling dat een promovendus het wiel opnieuw uitvindt.
Controleren of het rolt kan echter geen kwaad.
Vrij naar R. Chaigneau, 1995. In: De beste stellingen zijn van hout – uitspraken van Delftse promovendi. Technische Universiteit Delft.

10. Samen promoveren betekent in de praktijk dat het tevens het enige is dat je nog samen doet.

11. We all have wings, but some of us don't know why.
INXS (Kick, 1987).

12. In de toekomst mogen trekvogels waarschijnlijk alleen nog tijdens de randen van de nacht over de waddenzee vliegen.

Stellingen behorend bij het proefschrift:

Drying of willow biomass in supply chains

Jörg Gigler

Wageningen, 24 januari 2000

Voor mijn moeder

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Account:

Parts of this thesis have been or will be published in international scientific journals. Chapter 2 consists of an article published as *Biomass and Bioenergy* 1999:17:185-198. The papers corresponding with Chapters 3-6 have been submitted to various journals. Reference should be made to the original article(s). For the purpose of this thesis, the references of all chapters were pooled (see reference section, p. 117).

1

General introduction

During the energy crises of the seventies, the world awoke from its fossil fuel dream and recognised the potentials of renewable energy sources such as wind, solar energy, hydropower and biomass. At first, the need for renewables was urged by the dependence of the major industrial nations on fossil fuels. Today, the interest in renewable energy is mainly prompted by the need to reduce the output of CO₂ and other so-called 'greenhouse gases' to prevent global warming [Hall et al., 1997; Hall and Scrase, 1998; Nabuurs and Verkaik, 1999]. The Dutch Government has set a target to replace 10% of domestic energy consumption by renewable energy by the year 2020 [Ministry of Economic Affairs, 1997]. Moreover, within the European Union, the Netherlands' target is 6% renewable energy of the domestic energy consumption for the period 2008-2012 [Kram and Van Rooijen, 1998].

Biomass is a collective noun for products of recent organic origin, such as wood and agricultural residues [Sipilä, 1993; Faaij, 1997]. Of the present global energy consumption, 13 to 14% is derived from biomass [Hall and Scrase, 1998]. Biomass can be used as a fuel in energy plants for the generation of electricity and heat. Biomass fuel has a closed carbon cycle and therefore is a renewable source of energy. A tree, for example, takes up CO₂ for its growth. During use as a biomass fuel, CO₂ is released again as one of its breakdown products. Thus, apart from CO₂ emissions caused by production, logistics and conversion of biomass, the net release of CO₂ is zero [Nabuurs and Verkaik, 1999]. By source of origin, biomass fuels can be grouped into:

- *Waste products*: products that are usually dumped or left at their source, such as demolition wood, sewage sludge and forest thinnings. Due to Dutch regulations that make dumping of organic material expensive, waste products may have a negative cost price as biomass fuel.
- *By-products*: products which, due to their low market price, become available as biomass fuel but which can also be used for other purposes. By-products are often of agricultural origin, e.g. straw and foliage.
- *Energy crops*: crops which are specifically grown to produce biomass fuel. Examples are short rotation coppice (willow, poplar), miscanthus and hemp.

In the Netherlands, at present, waste and by-products attract most attention from energy producers because of their low or even negative price. Interest in energy crops is low due to their high cost price. It is not certain, however, whether the total amount of waste and by-products in the Netherlands in the future will be sufficient to meet expected demands for biomass fuel [Van den Heuvel and Gigler, 1998]. Thus, energy crops may become an option. In countries like Sweden and Great Britain, energy crops (mainly willow) are already grown on a commercial scale [Larsson et al., 1998; Pitcher et al., 1998]. For agriculture, energy crops can be an alternative to common agricultural crops like grain, potatoes and sugar beet, which prices are

constantly under pressure [Hanegraaf et al., 1998]. If the price at which energy crops are offered can be reduced, they will attract (more) interest from energy producers.

Willow short rotation coppice

In this thesis, tools are developed to reduce the costs of biomass fuels. Willow short rotation coppice (*Salix viminalis* L.) is chosen as an example because willow represents woody biomass fuels as well as energy crops.

Willow has a life cycle of 20 to 25 years [Culshaw and Stokes, 1995]. In North-west Europe, harvest takes place every three to five years, between November and April. In moderate climates (like in the Netherlands, Denmark and South Sweden), the expected maximum yield of willow is currently 8 to 12 tons DM per ha (DM=Dry Matter) annually, under favourable growing conditions [Larsson et al., 1996]. At harvest, the willow crop is homogeneous because all trees of one field are planted at the same time. Accordingly, all stems have approximately the same size and shape which accommodates product characterization and modelling of processes in the supply chain. For most field operations (such as planting, weeding and crop protection), common agricultural equipment can be used [Coelman et al., 1996]. However, for harvest, special equipment is required. Harvest is an important operation in the supply chain of willow to an energy plant because harvest marks the transition of an energy crop into a biomass fuel. For willow, three harvest techniques exist (Table 1; Figure 1): harvest as chips, chunks or whole stems (which will hereafter be referred to as stems) [Mitchell and Hudson, 1994; Culshaw and Stokes, 1995; Hartmann and Thuneke, 1997].

For energy conversion, chips are usually required. In some cases chunks are acceptable. The exact fuel specifications depend on the energy conversion technology [Van den Heuvel et al., 1994; Stassen, 1994; Van den Broek et al., 1996; Dumbleton, 1997]. Thus, if willow is not harvested as chips, size reduction may be necessary to yield a suitable biomass fuel. At harvest, the moisture content of willow is about 1 kg water per kg DM [Kofman and Spinelli, 1997; Nellist, 1997b]. The high moisture content causes several problems:

- Long term storage of chips, which is necessary when energy plants request year round supply of willow fuel, may lead to high dry matter losses and environmental and health risks due to microbial degradation [Thörnqvist, 1985; Mitchell et al., 1988; Gislerud, 1990; Jirjis, 1995a; Kofman and Spinelli, 1997; Nellist, 1997b].
- A high moisture content reduces the conversion efficiency of willow into electricity and increases gaseous emissions due to lower boiler temperatures [Riley and Drechsel, 1983; Lyons et al., 1989; Liang et al., 1996; Scholz and Gläser, 1997].

- Water, in excess of the moisture content specified by the energy plant, needs to be transported and handled which causes additional costs and environmental problems.

To reduce the disadvantages and risks associated with a high moisture content, drying is strongly recommended.

Table 1: Advantages and disadvantages of harvest techniques for willow biomass.

Technique	Size (mm)	Advantages	Disadvantages
Chips	0-50	<ul style="list-style-type: none"> • desired particle size for energy conversion • high bulk density • easy handling • multiple use of harvest machinery 	<ul style="list-style-type: none"> • storage problems at high moisture content (high DM-losses, health risks) • (covered) storage can be expensive
Chunks	50-250	<ul style="list-style-type: none"> • natural drying possible • no storage problems (low DM-losses) • desired particle size, depending on energy plant • easy handling 	<ul style="list-style-type: none"> • size reduction to chips may be necessary • requires special harvest machines
Stems	5,000 to 8,000, not reduced in size	<ul style="list-style-type: none"> • natural drying possible • no storage problems (low DM-losses) • cheap storage possible • field transport equipment may not be necessary 	<ul style="list-style-type: none"> • size reduction to chips or chunks necessary • handling difficult • low bulk density • requires special harvest machines

Supply chain of willow biomass

The supply chain of willow biomass to an energy plant consists of a series of actions that should take place to change the willow coppice at the field into a suitable biomass fuel at the energy plant. The fuel characteristics should comply with the fuel specifications laid down by the energy plant. In this thesis, the supply chain is defined to start at willow harvest and to end at the energy plant, when the fuel should meet the plant's specifications.



Figure 1: Harvest of willow stems (top) and storage of willow chunks (bottom, right) and stems (bottom, middle).

To reduce the cost price of willow biomass fuel, different possibilities exist. These include reducing the cost of growing willow, combining the growth of willow fuel with nature management and other land uses or production of fibres and chemicals for industry [Van den Heuvel and Gigler, 1998]. In the supply chain of willow to an energy plant, many choices have to be made. Which harvest technique should be applied? Where and how should storage take place? How should the willow fuel be dried? Where should size reduction take place? One method of reducing the cost price of willow is by optimization of the supply chain, which means selecting supply chains which deliver the fuel to the energy plant at minimum costs [Huisman and Gigler, 1997]. In comparison, for example, to the reduction of production costs by breeding high productive willow clones, cost reduction measures in the supply chain can be implemented relatively quickly.

In this thesis, the willow supply chain includes the following actions:

- *harvest* as chips, chunks or stems;
- *storage*, when the willow fuel is not needed immediately after harvest;
- *size reduction*, when the particle size after harvest does not comply with the fuel specifications laid down by the energy plant;
- *drying*, to reduce the moisture content of willow to meet the plant's specifications or to enable long term storage;
- *transportation*, to move the willow biomass fuel from the harvest site to the energy plant, or to a storage or processing site for size reduction or drying.

In the chain, the position of both harvest and energy conversion is fixed. The time span between harvest and energy conversion is variable. Storage, size reduction, transport and drying can take place in random order (Figure 2).

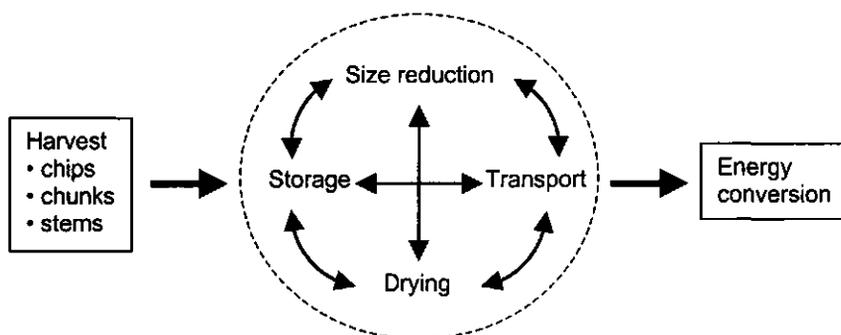


Figure 2: General design of the willow biomass supply chain.

A supply chain may be designed by selecting all actions which are necessary to reach the target specifications set by the energy plant and putting these actions in a

particular order. When the costs of all actions are known, the supply costs can be calculated. A simulation model of the supply chain can be a useful tool in comparing all possibilities. A disadvantage of simulation is that the cost of all possibilities has to be calculated. At the end, the cheapest option is selected. The use of an optimization tool which calculates the optimum solution (in this case, the cheapest chain design) is more convenient. Such a tool can be applied to different types of biomass fuels.

Different studies exist on the supply chain of willow and related woody biomass fuels [Mitchell et al., 1995; Allen et al., 1997; Vodder Nielsen et al., 1997; Sims and Culshaw, 1998]. These studies are restricted to a few options in the supply chain only. Usually, drying options other than natural drying are not included. Supply chains are also compared which have different initial characteristics and target fuel specifications. The limitations of different approaches reported in literature hinder a useful comparison of supply chains and costs.

Drying of willow biomass

To design minimum cost supply chains and calculate supply costs, it is necessary to gain insight into the different drying methods of willow and their associated costs. The cost of storage and drying can be very high [Sims and Culshaw, 1998]. According to Vodder Nielsen et al. [1997], these costs can amount to up to two thirds of the total handling costs at the plant. The drying techniques of willow biomass are closely linked to the harvest techniques which determine the particle size. The particle size of stems and chunks can be reduced to that of chips to enable forced or thermal drying, but this reduction causes additional supply costs. In this thesis, three drying options are distinguished:

- *Natural wind drying* which takes place in large piles during outdoor storage. The weather conditions and product characteristics largely determine the drying time. Natural wind drying is only relevant for stems and chunks. For chips, internal heating due to microbial activity will cause high dry matter losses, while the moisture content hardly changes, or may even increase [Gislerud, 1990; Gigler et al., 1996; Kofman and Spinelli, 1997].
- *Forced convective drying* which takes place by forcing ambient air through the material to be dried. On farm drying facilities (for potatoes and grain) can be used for willow. Forced convective drying is only relevant for chips and chunks [Arola, 1988; Gustafsson, 1988; Mivell, 1988; Pringle and Pan, 1991; Nellist, 1997b]. For stems, the release of moisture is slow, which causes high forced drying costs.

- *Thermal drying* which takes place using heated air of up to a few hundred degrees Celsius in a drying installation. For an efficient drying process, a small particle size is required [Van 't Land, 1991; Pierik and Curvers, 1995].

A wide range of studies exist on the storage and drying of woody biomass. These studies give detailed information on DM-losses, growth of micro-organisms, the best way to store et cetera [Gigler et al., 1996]. For willow, a few studies exist on storage and drying [Lyons et al., 1989; Kofman and Spinelli, 1997; Nellist, 1997b]. Most studies mainly describe initial and final moisture contents in large scale drying experiments. In some cases, intermediate moisture measurements were conducted. However, in order to investigate the prospects of different drying options, knowledge of the drying processes under variable ambient air conditions (as a function of the drying time) is necessary. Then, the parameters governing the drying processes can be investigated. These results can be used for supply chain optimization in order to reduce the costs of providing biomass fuels to energy plants.

Objectives

This thesis investigates supply chains of biomass fuels to energy plants where the fuel specifications should be met at minimum costs. To investigate drying of biomass fuels in the supply chain, models were developed to gain insight into the parameters governing the drying process. Willow biomass was chosen as the test sample. The main objectives were:

1. To develop an optimization tool to determine minimum cost supply chains of willow biomass to energy plants.
2. To develop models to quantitatively describe the drying process of willow biomass and to investigate the parameters which govern this process.
3. To provide general supply strategies which deliver willow biomass to energy plants (according to the plant's fuel specifications) at minimum costs.

Outline of the thesis

In Chapter 2 minimum cost supply chains of willow biomass to energy plants are determined with a simulation model. All possible actions in the supply chain of willow biomass are described and the costs are calculated. The influence of the time span between harvest and energy conversion on the selection of optimal chains and the supply costs is investigated and supply strategies are derived.

Based on these strategies, drying methods in the supply chain of willow are investigated. Chapter 3 discusses drying characteristics of willow at particle level.

For chips and stems, drying processes are described by diffusion models and validated experimentally. The diffusion models are incorporated into the bulk drying models of Chapters 4 and 5. Chapter 4 presents a deep bed drying model of chips to investigate the forced convective drying process of a willow chip bed. The model is validated by bulk-drying experiments. The possibilities and costs of using farm facilities for willow drying are assessed. Chapter 5 discusses the natural wind drying process of willow stems in large piles. Results of large scale drying experiments are statistically analysed and compared with drying model simulations.

In Chapter 6, a general methodology for optimization of supply chains by Dynamic Programming is presented. Finally, in Chapter 7 (Discussion and conclusions), drying of willow chunks is discussed. Furthermore, the new information in this thesis on drying of willow biomass is incorporated into the optimization model of Chapter 6, and the supply strategies derived in Chapter 2 are evaluated.

2

Willow supply strategies to energy plants

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Gerrit Meerdink
Eligius MT Hendrix*

Abstract

The main objective of this study was to develop minimum cost supply strategies for willow to energy plants (two plant sizes: 0.5 and 30 MW_e, two energy conversion technologies: combustion and gasification). Time span between harvest and energy conversion varied from 1 to 12 months. For a realistic comparison, different supply chains were based on the same initial characteristics (i.e. moisture content 50% wb at harvest) and final fuel specifications at the energy plant (moisture content 20% wb, particle size chips or chunks). Cost calculations were based on the integral cost calculation method and were presented for all process steps. The main conclusion was that the time span between harvest and energy conversion and the size and conversion technology of the energy plant largely influence the design of the supply chain and consequently the supply costs. The fuel supply costs ranged from 17.6 to 26.1 ECU/t DM or 0.010 to 0.023 ECU/kWh. The cost reduction which could be achieved by choosing the minimum cost chain design could be as high as 45% or 14.4 ECU/t DM. Generally, the strategy of minimum costs for supply of fuel to an energy plant running all year round on willow was as follows:

- for farmers who should supply their willow within six months after harvest: harvest as chips, forced drying at the farm and transport (if necessary);
- for farmers who should supply their willow beyond six months after harvest: harvest as chunks or stems, natural drying near the willow field, transport (if necessary) and central chipping (if applicable).

1 Introduction

In North-west Europe, willow coppice (*Salix viminalis*) has great prospects as a biomass fuel. It is already grown on a large scale in Sweden [Larsson et al., 1996]. Willow coppice is a woody crop with a life cycle of 20-25 years which has an expected maximum yield of 8-12 tons dry matter per ha (t DM/ha) annually under favourable growing conditions. At harvest, which takes place every three or four years between November and April, the moisture content is around 50% wb^{*}.

Willow as a biomass fuel is currently more expensive than fossil fuels. The production costs of energy from willow biomass are mainly determined by [Coelman et al., 1996]:

- crop production costs (including costs of land, farmers' income etc.);
- supply costs to the energy plant (including all links or process steps of the supply chain);
- production costs of energy at the energy plant.

The fuel supply costs of willow are in the range of 10 to 20% of the total costs, depending on the conversion technology, plant size, transport distance, etc [Coelman et al., 1996]. The supply chain of willow begins at harvest and ends at the

^{*} moisture contents are expressed on a wet base (wb; kg water/kg total)

energy plant when the fuel is ready for conversion. The supply chain can include the following process steps: harvest, storage, drying, size reduction, transport and handling. Before conversion of biomass to energy takes place, the characteristics of the willow fuel must meet the physical, chemical and other specifications of the energy plant. The most important physical fuel specifications are moisture content and particle size and both can be influenced in the supply chain. Consequently, many choices have to be made in the supply chain. For instance, how should willow be harvested in order to be delivered at minimum costs at the energy plant? By selecting minimum cost supply chains for specific situations, cost reductions can be achieved and the feasibility of energy crops as an alternative to fossil fuels may be improved.

In literature, several studies have been reported on biomass supply chains to energy plants [Mitchell et al., 1990; Allen et al., 1997; Vodder Nielsen et al., 1997; Sims and Culshaw, 1998]. In most studies, different supply chains are compared with each other but the comparison is often biased by differences in characteristics of the fuel eventually delivered at the energy plant. Furthermore, many studies do not take the time span between harvest and energy conversion into account. This time span can have a considerable effect on the costs of the supply chain. Also it should be clear which cost data are used and how they were calculated [Mitchell et al., 1995]. The main objectives of this study are:

1. to calculate and compare costs of different supply chains of willow coppice to energy plants;
2. to select minimum cost supply chains and derive supply strategies;
3. to calculate the cost reductions which can be achieved by selecting minimum cost supply chains.

2 Methodology

The supply chain of willow starts at harvest. Then the initial moisture content is assumed to be 50% wb for all chains. To enable a correct comparison, all supply chains should deliver the willow fuel at the energy plant according to the same specifications. Although in reality a wide range of moisture contents can be delivered, in this study it is assumed that the moisture content for energy conversion should be 20% wb. Energy conversion is limited to two conversion technologies (combustion and gasification) and two plant sizes (small and large scale, 0.5 and 30 MW_e respectively). With respect to the particle size requirements, it is assumed that for combustion chips or chunks are required and for gasification chips only (see Table 2 for references).

The supply chain consists of many links or process steps. In this study, the following were incorporated:

- harvest (as chips, chunks or stems)
- natural drying (on the headland, on gravel)
- storage (on the headland, on gravel, with or without cover)
- forced drying (on gravel, covered)
- size reduction [at the farm (=decentral), at the plant (= central)]
- transport (by truck) and handling
- thermal drying (with a drum dryer)

Machine costs are calculated according to the integral cost calculation method, using values which are relevant to the situation in the Netherlands [Oving, 1984; Meeusen-van Onna, 1997]. In Table 3, cost factors determining the machine costs are shown. Where possible, the use of common agricultural equipment is assumed and costs made specifically for willow only are assigned to the chain (e.g. a tractor or a fan). For prototype equipment, information from literature and manufacturers is used. Large machines (like harvesters) are assumed to be operated by contractors because the machines are usually too expensive for economic use by one farmer only. To enable a relevant comparison, cost calculations of machines which can only be used for willow (like harvesters) are based on full utilization. Furthermore, it is assumed that harvest takes place every four years with an average yield of 40 t DM/ha.

For each combination of plant size and conversion technology, a few chain designs are selected (Table 1) and compared to each other with the following main restrictions:

- forced drying of chips and chunks takes 1 month; for stems, forced drying is not incorporated because the bark prevents a quick release of water which would result in inefficient drying; after drying, for chips and chunks covered storage is necessary to prevent rewetting;
- at small scale plants, central size reduction as well as thermal drying is not incorporated because the total amount of fuel is too small to enable profitable use of large scale comminution or thermal drying equipment;
- for small scale plants, transport is not necessary because the plant is located near the willow fields.

For storage and drying, many possibilities exist but the cheapest option only is incorporated in the supply chain to obtain a chain with minimum costs (for instance, storage and drying in a pile, covered with plastic and situated on gravel is cheaper than drying in a potato store). The supply costs are expressed in ECU/t DM¹ and

¹ 1 ECU = 1.09 US\$ (March 1998) ≈ 1 EURO

ECU/kWh. The time span between harvest and energy conversion varies from 1 to 12 months. To compare all supply chains, a cost calculation model is developed. Separate models are incorporated to calculate the drying costs.

Table 1: Overview of chain designs selected for calculation.

No.	harvest	natural drying	decentral size reduction	forced drying	transport	central size reduction	thermal drying
<i>Small scale combustion</i>							
A1	stems	(x)	x	(x)	-	-	-
A2	chunks	(x)	-	(x)	-	-	-
A3	chunks	-	-	x	-	-	-
A4	chips	-	-	x	-	-	-
<i>Small scale gasification</i>							
B1	stems	(x)	x	(x)	-	-	-
B2	chunks	(x)	x	(x)	-	-	-
B3	chips	-	-	x	-	-	-
<i>Large scale combustion</i>							
C1	stems	x	x	-	x	-	(x)
C2	stems	x	-	-	x	x	(x)
C3	stems	(x)	x	(x)	x	-	-
C4	chunks	x	(x)	-	x	-	(x)
C5	chunks	x	-	-	x	(x)	(x)
C6	chunks	(x)	-	(x)	x	-	-
C7	chunks	-	-	x	x	-	-
C8	chips	-	-	-	x	-	x
C9	chips	-	-	x	x	-	-
<i>Large scale gasification</i>							
D1	stems	x	x	-	x	-	(x)
D2	stems	x	-	-	x	x	(x)
D3	stems	(x)	x	(x)	x	-	-
D4	chunks	x	x	-	x	-	(x)
D5	chunks	x	-	-	x	x	(x)
D6	chunks	(x)	x	(x)	x	-	-
D7	chunks	(x)	-	(x)	x	x	-
D8	chips	-	-	-	x	-	x
D9	chips	-	-	x	x	-	-

x: operation always done; (x): operation done if possible or necessary;

-: operation not applicable.

3 Input data

3.1 Energy conversion

The small scale plants (0.5 MW_e) are located near the willow fields, the large scale plants (30 MW_e) are located 50 km from the willow fields. Characteristics and references are presented in Table 2.

Table 2: Data of energy plants [Van den Heuvel et al., 1994; Faaij et al., 1995; Van den Broek et al., 1995; Van den Broek et al., 1996; Dumbleton, 1997; Van Doorn, 1997].

Technology Scale	Combustion		Gasification	
	Small	Large	Small	Large
Size (MW _e)	0.5	30	0.5	30
Efficiency (%)	20	30	22.5	42
Utilisation (h/y)	6,000	8,000	6,000	8,000
Fuel need (t DM/y) ^a	2,939	156,730	2,612	111,950
Particle size needed	chip/chunk	chip/chunk	chip	chip
Transport distance (km)	0	50	0	50

^a Yearly amount of fuel based on a moisture content of 20% wb

The annual fuel need depends on plant size and conversion technology: gasification is more efficient than combustion so less fuel is needed to produce the same amount of electricity. Since this study focusses on supply chains, basically only the amount and specifications of fuel needed are relevant.

3.2 Harvest

The particle size of the fuel entering the supply chain is determined by the harvest technique. Three possibilities are considered: harvest as chips (size 0-50 mm), chunks (50-250 mm) and whole stems (up to 8 m). The bulk density of chips, chunks and stems is 160, 145 and 80 kg DM/m³ respectively [Gigler et al., 1996]. Cost calculations are presented in Table 3 (data columns 1, 2 and 3). The choice of harvesters is restricted to large scale machines only which have been tested in various field trials (references given with machine description).

Willow chips are assumed to be harvested with the CLAAS twin row willow harvester which is basically a forage or maize chopper, equipped with a special willow header which cuts the stems from the stools.

Table 3: Costs of harvest, transport, handling and size reduction of willow.

Equipment	Harvesting			Transport			Handling			Size Reduction		
	Claas	Austofft	Segerslätt	Tractor ¹	Trailer ¹	Shovel	Crane	S/M	Tractor ¹	Large		
Purchase (ECU) ^a	216,216	216,216	225,225	76,171	15,541	135,135	168,919	45,045	76,171	225,225		
Resale value (ECU) ^b	21,622	21,622	22,523	7,617	1,554	13,514	16,892	4,505	7,617	22,523		
Lifetime (y)	5	5	5	12	12	12	12	5	6	2		
Utilisation (h/y)	1000	500	500	800	400	9,600	9,600	1600	1600	4000		
Depreciation (ECU/y)	38,919	38,919	40,541	5,713	1,165	10,135	12,669	8,108	11,426	101,351		
Interest (ECU/y) ^c	7,771	8,094	8,431	2,895	614	5,137	6,421	1,619	2,868	8,326		
Maint.+ Ins. (ECU/y) ^d	17,297	9,730	10,135	3,123	264	5,541	6,926	3,604	3,123	18,018		
Fuel (ECU/y) ^e	16,278	4,115	2,897	3,678	-	6,306	6,306	-	7,357	45,405		
Storage (ECU/y) ^f	214	214	214	107	160	214	214	53	107	-		
General (ECU/y) ^g	7,568	7,568	7,883	2,666	544	4,730	5,912	1,577	2,666	7,883		
Machine (ECU/h)	88.05	137.27	140.20	22.73	7.06	40.08	48.06	9.35	17.22	45.24		
Contractor (ECU/h) ^h	15.41	24.02	24.54	3.98	1.23	7.01	8.41	1.64	3.01	-		
Labour (ECU/h)	20.27	20.27	20.27	20.27	-	20.27	20.27	-	20.27	-		
Total (ECU/h)	123.73	181.57	185.00	46.97	8.30	67.36	76.74	10.98	40.50	45.24		

^a [Balk-Spruit and Spigt, 1994; Van der Meijden and Gigler, 1994; Devobo, 1997; OBMtec, 1997; Segerslätt, 1997; Vermeer, 1997]

^b Resale value is 10% of purchase price [Balk-Spruit and Spigt, 1994]

^c Interest rate: 7% [Balk-Spruit and Spigt, 1994]

^d Maintenance: 3.5% of purchase price for harvesting and size reduction equipment, 3.1% for tractor and handling equipment, 1.7% for trailer, 7% for large scale size reduction equipment [Balk-Spruit and Spigt, 1994]

^e Fuel price: 0.32 ECU/litre, electricity: 0.05 ECU/kWh (Oct. 1997)

^f Storage costs depend on the space required; harvesting and handling equipment 20 m², tractor 10 m², trailer 15 m², small/med. size reduction equipment 5 m². Storage costs: 10.70 ECU/m² [Balk-Spruit and Spigt, 1994]

^g General costs (road taxes, electricity, etc.): 3.5% of the purchase price [Balk-Spruit and Spigt, 1994]

^h Contractor costs: 17.5% of machine costs [Balk-Spruit and Spigt, 1994]

ⁱ Tractor power 100 kW

^j Trailer: 12 t, tandem axles

After comminution, the chips are deposited into a trailer towed by a tractor driving next to the harvester (cost calculations in Table 3, columns 4 and 5). Three tractors and trailers are necessary to transport the willow chips to a waiting truck on the headland or to the farm. In literature, a wide range of harvest productivities are reported (0.75-2.6 h/ha) [Van der Meijden and Gigler, 1994; Spinelli and Kofman, 1996; Hartmann and Thuneke, 1997]. In the calculations an average productivity of 1.7 h/ha was used. The total harvesting costs were 12.31 ECU/t DM.

Willow chunks are assumed to be harvested with the Austofft twin row willow harvester which is based on a sugar cane harvester. The same productivity and transport capacity as for chips are assumed [Van der Meijden and Gigler, 1994; Spinelli and Kofman, 1996]. The total harvesting costs were 14.76 ECU/t DM.

Willow stems are assumed to be harvested with the Segerslätt Empire 2000 stem harvester. This machine cuts the willow trees at the stump with two circular saw blades. Rubber belts convey the stems to a bunker at the back of the machine which is unloaded on the headland of the field. On the field no transport equipment is needed. The capacity is 3 h/ha [Gigler and Sonneveld, 1998]. The total harvesting costs were 13.88 ECU/t DM.

3.3 Size reduction

Size reduction of stems and, in some cases, chunks is necessary to match the particle size specifications at the energy plant. Two size reduction operations are incorporated: chipping (reduction to chips) and chunking (reduction to chunks). The productivity of chunking is 20-30% higher compared to chipping [Danielsson, 1990]. Size reduction can take place decentrally (at the field, for small scale plants) or centrally (at large scale energy plants).

For decentral size reduction, it is assumed that a small/medium scale chipper which is linked into the hitch of the tractor is used. According to manufacturers, the average productivity is approximately 4 t/h (load factor 70%) [OBMtec, 1997; Vermeer, 1997]. For decentral chunking, the productivity is 25% higher (5 t/h) [Devobo, 1997]. The decentral size reduction costs were 12.87 ECU/t DM for chipping and 10.30 ECU/t DM for chunking (Table 3, columns 8 and 9).

For central size reduction, the use of a fully-mechanised large scale drum chipper which is fuelled by electricity is assumed. Supervision is done by personnel of the energy plant. Consequently, labour costs are not incorporated for central size reduction because personnel is only required incidentally (for instance during breakdowns) which means that labour input and thus labour costs are very low compared to machine costs. According to manufacturers, the productivity of large scale equipment is approximately 16 t/h (load factor 90%) [OBMtec, 1997; Vermeer, 1997]. The total central size reduction costs were 2.83 ECU/t DM for chipping and

2.26 ECU/t DM for chunking (Table 3, column 10). For chipping chunks, it is assumed that the costs are half the costs of chipping stems because feeding chunks to a chipper is much easier and faster than feeding stems [OBMtec, 1997; Vermeer, 1997].

3.4 Storage

Storage of willow fuel is necessary due to year round demand. Basically storage can take place at the farm [on the headland, on gravel (covered), in a shed or potato store] or at the energy plant [on gravel (covered) or in a shed]. The storage costs depend on the location, type and period of storage and the bulk density of the willow fuel. Storage height is 4 m.

For free storage (without side walls), the volume to store stems is equal to the ground area multiplied by the height. For chips and chunks, the edges of the piles are not straight but are shaped like an elongated prism. It is assumed that the angles of the chunk and chip piles are 45° and the free space around all piles is 1 m. Based on piles of 40 t DM (the yield of 1 ha), the volume-to-area ratio (which is the volume of product which can be stored on 1 m²) is 2.1 m³/m² for chips and chunks and 3 m³/m² for stems. For 40 t DM, the ground area needed is 119 m² for chips, 131 m² for chunks and 167 m² for stems. Storage costs are presented in Table 4.

3.5 Drying

At harvest, the moisture content of willow is around 50% wb. For all supply chains, it is assumed that a moisture content of 20% wb is required at the energy plant which means that drying is necessary. Three possibilities are considered: natural, forced and thermal drying.

3.5.1 Natural drying. Natural drying is defined as drying which takes place during outdoor storage. The weather conditions largely determine the time necessary for drying. For chunks and stems, natural bulk drying is an interesting option because the air can easily penetrate the pile and dry matter losses will be low. For chunks and stems, the mean monthly drying rates were 5% absolute/month for both materials and DM-losses were 2 and 1%/month respectively [Jirjis, 1995b; Gigler et al., 1996; Nellist, 1996; Nellist, 1997a; Kofman and Spinelli, 1997; Gigler and Sonneveld, 1998]. It is assumed that DM-losses at a moisture content equal to or lower than 20% wb are negligible.

Table 4: Costs of different storage lay-outs for willow (pile height 4 m).

Storage location	Type of storage	Costs per unit (ECU/m ² .y)	Chips	Chunks	Stems
			(ECU/t DM.month)		
Farm	Headland ^a	0.05	0.01	0.01	0.02
	Gravel floor ^b	2.36	0.59	0.65	0.82
	Plastic sheet ^c	0.17	0.06	0.06	-
	Nylon cover ^d	0.95	0.32	0.35	-
	Shed ^e	9.07	2.23	2.48	3.16
	Potato store ^f	45.71	5.95	6.57	11.90
Energy plant	Gravel floor ^g	2.36	0.59	0.65	0.82
	Shed ^h	6.28	1.56	1.71	2.19

^a Assumption: willow is grown on a good quality soil (clayey/loamy)

^b Yearly costs of a gravel floor are 7.5% of total costs of 31.53 ECU/m² [Balk-Spruit and Spigt, 1994; Organization of Insurance brokers, 1996]

^c Price of plastic sheeting: 101.47 ECU/role (12x50 m) or 0.17 ECU/m² (one time use only) [Venturi et al., 1996]; for stems no cover is used

^d Price of nylon cover: 4.74 ECU/m². Estimated life time: 5 years [Venturi et al., 1996]

^e Size of shed is 25x50 m, height 5 m. Yearly costs are 9.5% of total costs of 95.50 ECU/m² [Misset, 1993; Balk-Spruit and Spigt, 1994; Organization of Insurance brokers, 1996]

^f Yearly costs of potato store of 900 t is 9.5% of mean cost price of 200.45 ECU/t which is 19.05 ECU/t. Per m² floor, 2.4 t of potato can be stored, the cost price of a potato store is 45.71 ECU/m² [Balk-Spruit and Spigt, 1994]

^g Assumption: same costs as on the farm

^h Size of shed is 50x50 m, height 5 m. Yearly costs are 9.5% of total costs of 66.08 ECU/m² [Balk-Spruit and Spigt, 1994; Organization of Insurance brokers, 1996]

3.5.2 Forced drying. Forced (convective) drying is defined as a process in which air (in this study ambient or slightly heated) is forced with a fan through the material to be dried. Usually the material is deposited on a perforated floor (e.g. a potato store) or on ventilation ducts. Drying costs consist of electricity costs (fan) and capital costs (ventilation ducts, cover, fan, gravel floor) (Table 5). The cheapest forced drying option is blowing drying air with a fan through ventilation ducts and through a nylon or plastic covered pile on a gravel floor. The pile height is 3 m. Drying costs are calculated as follows [Gustafsson, 1988]:

1. from the average temperature and relative air humidity for each month, the amount of water that the drying air can take up to the saturation point is calculated;
2. for the willow fuel, the total amount of water to be evaporated to reach a moisture content of 20% wb is determined;
3. from 1. and 2., the required amount of drying air is calculated;

4. from the pressure drop over the chips/chunks, the fan capacity and the number of fans necessary for 40 t DM are calculated;
5. the fan capacity is used to calculate the energy costs;
6. total drying costs are calculated by adding energy costs and capital costs.

Table 5: Costs of forced drying (pile height 3 m).

Type of Equipment	Costs per unit	Chips		Chunks	
		ECU/t DM.month			
Fan ^a	16.33 ECU/month	- ^h	- ^h	- ^h	- ^h
Electrical equipment ^b	6.49 "	- ^h	- ^h	- ^h	- ^h
Ventilation ducts ^c	10.81 "	0.27	0.27	0.27	0.27
Nylon cover ^d	0.08 ECU/m ² .month	0.41	0.41	0.46	0.46
Gravel floor ^e	0.20 "	0.77	0.77	0.85	0.85
Shed ^f	0.72 "	2.80	2.80	3.11	3.11
Potato store ^g	3.81 "	7.94	7.94	8.76	8.76

^a Yearly costs of fan 14.5% of total costs of 1,351.35 ECU; fan capacity: 38,000 m³/h³ [Balk-Spruit and Spigt, 1994]

^b Yearly costs of elec. equipment: 14.4% of total costs of 540.54 ECU [Balk-Spruit and Spigt, 1994]

^c Ventilation ducts are semicircular. Yearly costs are 540.54 ECU (14.4% of total costs) [Balk-Spruit and Spigt, 1994]. Assumption: length of 15 m enough for 40 t DM

^{d,e,f} Costs given in table 3; here adjusted to pile height of 3 m

^g Costs given in table 3; total costs for a shed with a pile height of 3 m are 90.81 ECU/m² [Balk-Spruit and Spigt, 1994; Segerslätt, 1997]

^h Number of fans and electrical equipment depends on moisture content of willow (amount of water to be evaporated)

3.5.3 Thermal drying. Thermal drying is defined as a process in which the material is dried with hot air (300 °C) in a drying installation. Different dryers are available (drum, CFB and steam dryers). The use of waste heat from the energy plant is also an option. In this study, a drum dryer located near the large scale energy plant is incorporated since this technology is proven and suitable for chips [Van 't Land, 1991]. The use of waste heat was not included because the technical possibilities, costs and consequences for the electrical efficiency are not clear. Thermal drying costs consist of energy costs and capital costs of the dryer. The calculation of the total thermal drying costs is based on Van 't Land and information from manufacturers [Van 't Land, 1991; Pierik, 1997]. The following methodology is adopted. Given the total amount of water to be evaporated to reach a moisture content of 20% wb:

1. energy costs are calculated from the energy needed for water evaporation;

2. the dimensions of the dryer and thus the capital costs are assessed;
3. the electricity costs to rotate the drum are calculated;
4. the total drying costs are found by adding 1, 2 and 3 and accommodating labour, building costs, etc.

3.6 Transport and handling

Transport costs are based on information from Dutch transport organizations [Remmers, 1996]. Stems are transported with a high volume truck (25.5 t, 120 m³, costs 0.995 ECU/km) and chips and chunks with a container truck (25.5 t, 80 m³, costs 1.0 ECU/km). Handling of chips and chunks is done with a shovel and of stems with a grapple crane [Feenstra et al., 1995]. The handling costs of chips, chunks and stems are 0.93, 1.04 and 2.13 ECU/t DM, respectively (Table 3, columns 6 and 7).

4 Results

In Figure 1, the minimum cost chain design (in ECU/t DM) is presented for small scale gasification to illustrate how the minimum cost supply chains are selected. For small scale combustion and large scale combustion and gasification, the minimum chain design is not presented in detail because the general trend is equal to the trend in Figure 1. In Table 6, the chain design with minimum supply costs is listed for each option of Table 1. Final results are presented in Figures 2 and 3.

Table 6: Minimum cost design of supply chains for small and large scale combustion and gasification as a function of the time span between harvest and energy conversion (codes refer to Table 1).

Months	1	2	3	4	5	6	7	8	9	10	11	12
Small scale combustion	A4	A4	A4	A2								
Small scale gasification	B3	B3	B3	B3	B3	B3	B2	B2	B2	B2	B2	B2
Large scale combustion	C9	C9	C9	C9	C6	C4						
Large scale gasification	D9	D9	D9	D9	D9	D5	D5	D5	D5	D5	D5	D2

For chunks and stems, up to a time span of 5 months, supply costs slowly decrease due to decreasing costs for forced or thermal drying because the moisture content decreases each month by natural drying. Between 5 and 6 months, supply costs decrease sharply because the desired moisture content of 20% wb is reached which means that no additional drying is required. Between 7 and 12 months, supply costs increase again due to storage. The minimum supply costs vary from 17.6 to 26.1

ECU/t DM. Regarding supply strategies to energy plants, for small scale gasification for a time span of 1 to 6 months, the chain design for chips is up to 34% (8.9 ECU/t DM) cheaper than for chunks and up to 45% (14.4 ECU/t DM) cheaper than for stems. For a time span from 7 to 12 months, the supply chain with chunks is up to 13% (3.8 ECU/t DM) cheaper than with chips and up to 15% (4.2 ECU/t DM) cheaper than with stems.

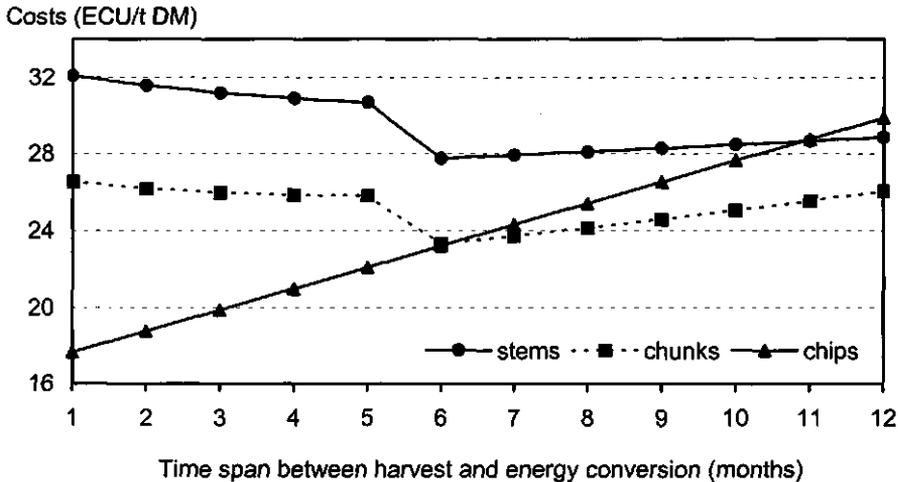


Figure 1: Supply costs of willow (ECU/t DM) to a small scale gasification plant as a function of the time span between harvest and energy conversion.

Figure 1 shows the minimum chain costs for each harvest technique (chips, chunks and stems). The chain design depends on the time span between harvest and energy conversion. For the first 6 months, minimum supply costs are obtained with chips (see also Table 6, second row) by the following chain design: harvest as chips and forced drying (no transport, because the plant is located near the willow fields). The chain costs increase with time because covered storage is necessary after forced drying. For months 7 to 12, minimum chain costs are obtained with chunks by the following chain design: harvest as chunks, natural drying and decentral size reduction to chips (no transport). Since the natural drying rate was assumed to be 5% absolute/month, no additional drying is necessary after 6 months storage because the moisture content has reached 20% wb.

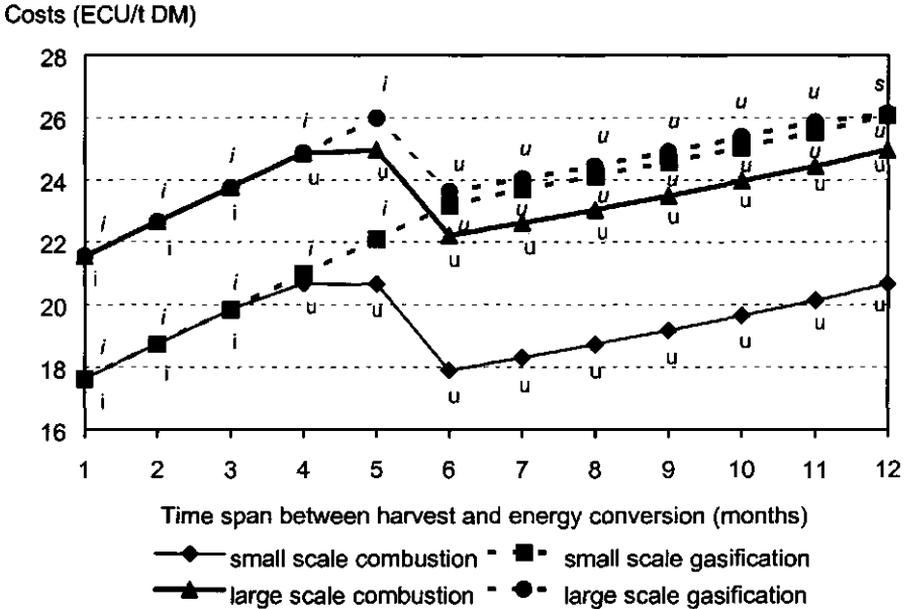


Figure 2: Supply costs of willow (ECU/t DM) as a function of the time span between harvest and energy conversion (*i*=chips, *u*=chunks, *s*=stems).

Figure 2 presents the minimum supply costs for all combinations of plant size and conversion technology. The same time dependency as described earlier was observed.

- For all options, for a time span of 1 to 3 months between harvest and energy conversion, the minimum cost chain design is harvest as chips, forced drying and transport (if necessary).
- For small and large scale combustion, for a time span of 4 to 12 months, the minimum cost chain design is harvest as chunks, natural drying, forced drying (in month 4 and 5 only) and transport (if necessary). The reason is that chunks are prone to natural drying and from month 4 onwards, enough natural drying has occurred to render the chunk chain the cheapest option (for months 4 and 5 combined with forced drying). From month 6 on, chunks have reached a moisture content of 20% wb by natural drying. Thus forced drying is superfluous and chain costs decrease rapidly. The supply costs slowly increase because of storage costs. The higher total chain costs of large scale combustion are due to increased transport costs.

- For small and large scale gasification, for months 5 and 6 the minimum cost chain design is harvest as chips, forced drying and transport (if necessary). From months 7 to 11, harvest as chunks, natural drying, transport (if necessary) and chipping (for small scale decentrally, for large scale centrally) have minimum chain costs. Because decentral chipping is much more expensive than central chipping, the total chain costs are close to each other for small and large scale gasification, despite transport costs for large scale plants. For month 12, the minimum cost chain design for large scale gasification is stem harvest, natural drying, transport and central chipping. For small scale gasification, the chain design after month 12 is equal to the chain design of months 7 to 11.
- Generally, it can be seen from Figure 2 that the supply chain for gasification is more expensive than for combustion because of the stricter particle size specifications of gasification plants.

Regarding supply strategies, for small scale combustion up to 31% (9.2 ECU/t DM), for medium scale combustion up to 26% (8.8 ECU/t DM) and for medium scale gasification up to 34% (11.1 ECU/t DM) can be gained by choosing the minimum cost chain design.

Table 7: Cost ranges for the supply chains of willow for different energy conversion options; ranges based on time interval (1 to 12 months).

Type of electricity plant	Costs (ECU/t DM)	Costs (ECU/kWh)
Small scale combustion	17.6 – 20.7	0.017 – 0.021
Small scale gasification	17.6 – 26.1	0.015 – 0.023
Large scale combustion	21.5 – 25.0	0.014 – 0.016
Large scale gasification	21.5 – 26.1	0.010 – 0.012

In Figure 3, the supply costs are presented for small and large scale combustion and gasification in ECU per kWh. Conversion costs are not included in the chain costs. Large scale gasification always entails the lowest chain costs because the high energy conversion efficiency and consequently lower total fuel need fully compensates for the higher chain costs per t DM. The second cheapest supply chain is for large scale combustion. The small scale conversion options yield the most expensive chains. For a time span up to 5 months, the cost difference (in ECU/t DM) between combustion and gasification is too small to be compensated for by the higher efficiency of gasification but for a time span from 6 to 12 months, the cost

difference (in ECU/t DM) is so small that gasification becomes the cheaper option (in ECU/kWh). The costs of the minimum cost chain designs are presented in Table 7.

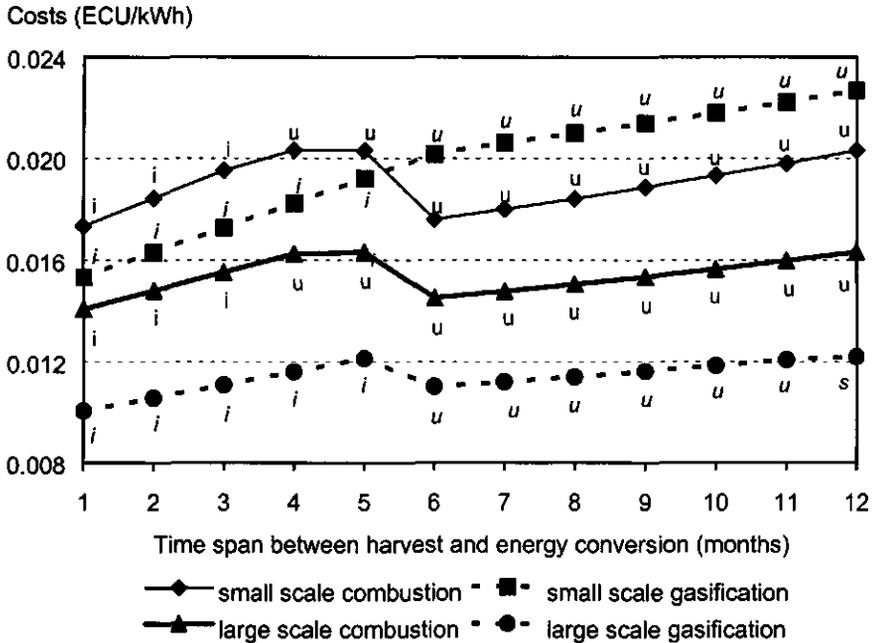


Figure 3: Supply costs of willow (ECU/kWh) as a function of the time span between harvest and energy conversion (i=chips, u=chunks, s=stems).

5 Discussion

In this study, the design of minimum cost supply chains is based on the physical characteristics of the biomass fuel which predominantly are moisture content and particle size. Besides physical characteristics, other characteristics (chemical, biological, etc.) determine the suitability of willow as a biomass fuel but the possibilities to influence those in the supply chain are very limited. Every process step influences the moisture content or particle size of the willow fuel until the final specifications of the energy plant are met. If fine particles instead of chips or chunks are required for a specific conversion technology, a new process step (grinding or milling) has to be added to the chain and the minimum cost chain design can be calculated again. Thus, the design of supply chains based on physical fuel characteristics is a useful tool for selecting minimum cost supply chains.

Data (costs, capacities, working hours, etc) for all process steps (harvest, storage, drying, size reduction, transport and handling) and for energy conversion are based on literature and information from manufacturers. Usually data are case-specific. Therefore, in this study average values and cost figures were used. The total supply costs will change when *different cost figures are used. However, the minimum cost design of the supply chain is very constant despite changes in cost figures.* For instance, higher harvest costs will increase the total chain costs but the chain design remains the same. A different willow yield (for instance 8 or 12 t DM/ha annually) influences the total chain costs but it will hardly affect the supply strategy. All links are expressed as ECU/t DM and lower or higher yields influence the links of different supply chains in the same way. However, different yields can affect the supply strategy when for instance harvest machines are not fully utilized anymore due to a lower yield but this study was based on the assumption of full utilization of equipment. The design of the supply chain is more sensitive to the fuel specifications of the conversion technology. If specifications are changed to a moisture content of 10% wb for example, total supply costs increase (more drying necessary) and natural drying of chunks or stems will become the cheapest option beyond 7 or 8 months after harvest.

Comparison of the results with other studies is difficult for two main reasons:

1. only the cheapest options possible were used in this study (because more expensive options would never lead to a minimum cost supply chain);
2. studies are usually based on national data and assumptions which differ between countries.

However, the general supply strategy of this study shows the same trend as the strategy reported by Vodder Nielsen et al. [1997].

For natural and forced drying, mean drying rates and DM-losses were obtained from literature. However, in wet months there will be little drying with bigger DM-losses and in dry months vice versa. By taking mean drying rates and DM-losses, these problems are circumvented. The predicted drying rate over a short period can be misestimated. For storage and natural and forced drying, different options are considered (on gravel, under a shed, uncovered, covered, etc.). It is assumed that different options have the same effect on the moisture content of the willow fuel although it is possible that different options cause different results (for instance, faster and more homogenous drying in a potato store compared to one single ventilation duct under a large pile). This study refrained from the option to utilize waste heat for forced or thermal drying. Although waste heat could reduce drying costs and thus the supply costs considerably, there exists uncertainty about the technical possibilities and the possible negative effect on the efficiency of electricity generation.

For long term storage, no interest costs are included. Supply chains are compared for the same number of months between harvest and energy conversion. The selection of the minimum cost supply chain is not influenced by the interest costs. However, for the final costs it should be kept in mind that interest was not included because in reality, the interest costs will increase the total supply costs.

In this study, harvest as chips and long term storage is not incorporated although it is common practice. According to the methodology presented here, long term storage of chips will never result in a minimum cost supply chain because no drying occurs during storage while dry matter losses are high [Gigler et al., 1996; Nellist, 1996; Kofman and Spinelli, 1997; Nellist, 1997a]. Thus in all cases, forced or thermal drying will be necessary to meet the specifications at the energy plant. Consequently, for chips only chains with forced drying immediately after harvest as chips, in order to avoid high DM-losses, were incorporated.

6 Conclusions

It can be concluded that the minimum costs design of the supply of willow to an energy plant depends on the time span between harvest and energy conversion and the size and conversion technology of the plant. For small and large scale combustion and gasification, the fuel supply costs range from 17.6 to 26.1 ECU/t DM and 0.010 to 0.023 ECU/kWh. It is important how costs are defined: for the willow supplier, the costs per t DM are relevant while for the energy producer, the costs per kWh output of the energy plant are more relevant. Our calculations have shown that a concerted approach of willow suppliers and energy producers with respect to the chain design is necessary to achieve the lowest total electricity costs from willow fuel.

The cost reduction which can be achieved by choosing the minimum cost chain design can be as high as 45% or 14.4 ECU/t DM. The harvest technique largely determines the chain design because harvest determines how the willow fuel enters the supply chain and which process steps are possible or necessary to deliver the willow fuel at the energy plant according to the fuel specifications. The possibilities of natural drying in the supply chain are important because they can reduce supply costs drastically if the time for drying is large enough to reach a moisture content of 20% wb which is around 5 to 7 months (depending on weather conditions).

Generally, the supply strategy with minimum costs to an energy plant running all year round on willow fuel is as follows:

- for farmers who should supply their willow within 6 months after harvest: harvest as chips, forced drying at the farm and transport (if necessary);

- for farmers who should supply their willow beyond 6 months after harvest: harvest as chunks or stems, natural drying near the willow field, transport (if necessary) and central chipping (if applicable).

If the total amount of fuel delivered to the energy plant is too small to allow the use of more than one large scale harvester (as for small scale combustion and gasification), the average supply costs for each harvest technique determine the minimum costs option. For chips, chunks and stems, the average supply costs over a 12 months period are for small scale combustion 23.7, 19.8 and 27.1 ECU/t DM, respectively, and for small scale gasification 23.7, 25.2 and 29.5 ECU/t DM, respectively. Thus, for small scale combustion, the cheapest option is harvest as chunks while for small scale gasification, the cheapest option is harvest as chips. It should be noted that under these conditions, farmers who deliver their fuel beyond 6 months after harvest never work with minimum cost supply chains.

Comparing chain designs for combustion and gasification, generally the supply chain for gasification is as expensive or more expensive than for combustion when costs are expressed in ECU/t DM due to stricter particle size requirements at the gasification plant (chips only). In ECU per kWh, generally supply costs for gasification are lower than for combustion due to higher efficiency of energy conversion which means a lower fuel consumption per kWh.

Comparing chain designs for small scale to large scale energy conversion, generally small scale is cheaper than large scale when costs are expressed in ECU/t DM due to increased transport costs for large scale. When costs are expressed in ECU per kWh, large scale is cheaper than small scale, due to the higher energy conversion efficiencies.

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Note added after publication

1. In this Chapter: drum dryer should read rotary dryer
2. In Table 3, in columns 6 and 7 (handling), row 4 (utilisation): 9,600 should read 800

3

Drying characteristics of willow chips and stems

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Abstract

Drying characteristics of willow (*Salix viminalis*) chips, and willow stems, with and without bark were investigated. The drying process was described with a diffusion equation. The effective diffusivity was described as a power law relation of the moisture concentration. Drying of a chip and of a stem without bark could be successfully described with a diffusion equation for a plane sheet and a cylinder, respectively, with diffusivity $D_G=(3.0\pm 1.0)*10^{-10}$ m².s⁻¹ and power law coefficient $a=0.3\pm 0.1$ (chip) and 0.3 ± 0.2 (stem without bark). Because the effective diffusivity increased with the moisture content, a was positive. Drying of a willow stem with bark could be successfully described as drying of a willow stem without bark, surrounded by a thin layer (bark) with a much lower diffusivity ($D_{bark}=(2.25\pm 0.25) *10^{-12}$ m².s⁻¹ and $a_{bark}= -0.4\pm 0.1$). The effective bark diffusivity increased with decreasing moisture content, due to bark shrinkage, and a decreasing resistance of the bark to water transport. Consequently, a_{bark} was negative. Compared to a willow chip, a willow stem without bark dried approximately 10 times slower from fresh state to equilibrium moisture content, mainly due to the larger diffusion distance. A stem with bark dried approximately 10 times slower than a willow stem without bark due to the low bark diffusivity.

1 Introduction

Willow short rotation coppice (*Salix viminalis*) can be used as a biomass fuel in an energy plant [Gigler and Annevelink, 1998]. At harvest, the moisture content of willow is approximately 1 kg water.(kg DM)⁻¹ (DM = Dry Matter). For safe storage of chips, the moisture content should preferably be less than 0.25 kg water.(kg DM)⁻¹. A low moisture content has a positive effect on boiler efficiency and on gaseous emissions [Van den Broek et al., 1995; Liang et al., 1996]. Consequently, drying is advisable. During harvest, a choice has to be made with respect to the harvest technique. Harvest as chips or stems are the most common techniques. The harvest technique determines the drying possibilities in the supply chain to an energy plant, and thus, greatly influences the supply costs [Gigler et al., 1999a].

To gain more insight into the drying of willow, the drying characteristics of the willow material are investigated. Several studies were reported in literature which investigated drying and storage of wood fuels [Mitchell et al., 1988; Gislerud, 1990; Gigler et al., 1996; Kofman & Spinelli, 1997]. However, these studies focussed mainly on experimental work without describing the fundamental drying processes. In addition to results from drying experiments with willow, Nellist [1997b] described the drying process of willow chips with an empirical relation. The advantage of an empirical relation is simplicity. The disadvantage is lack of anchorage in real physical parameters, so the effect of different external conditions is more difficult to accommodate. For drying of wood cylinders, modelling work was reported by Schmalko et al. [1998], but no attempts to model the drying process of wood stems

with bark have been reported. The objectives of this study are the provision of drying models for a willow chip and for a willow stem which are calibrated with experimental data.

2 Wood drying theory

During drying of wood, water is transferred at the interface between product and drying air [Crank, 1983; Strumillo and Kudra, 1986]. The mass flux ϕ_m of water is driven by the difference between the moisture concentration of the air at the wood surface $\rho_{a,i}$ and the drying air $\rho_{a,b}$:

$$\phi_m = k(\rho_{a,i} - \rho_{a,b}) \quad (1)$$

Simultaneously, a heat flux ϕ_q takes place due to a difference in temperature between the air in the boundary layer $T_{a,i}$ and the bulk air $T_{a,b}$ which, under adiabatic conditions, supplies the energy necessary for evaporation:

$$\phi_q = \alpha(T_{a,i} - T_{a,b}) \quad (2)$$

Between the mass and heat transfer coefficients, respectively k and α , the following relation exists [Strumillo and Kudra, 1986]:

$$\frac{\alpha}{k} = \rho_a c_{pa} \left(\frac{a_{lh}}{D_a} \right)^n \quad (3)$$

where n depends on the particle geometry (plane sheet: $n=0.67$; cylinder: $n=0.6$). For specific situations, empirical relations for $Nu = f(Re, Pr)$ are available to calculate the heat transfer coefficient. These relations are presented in Table 1 for a plane sheet and a cylinder.

During a drying process, two periods can be distinguished. In the first so-called constant drying rate period, the water activity a_w at the surface of the wood is equal to one (i.e. the water vapour concentration at the surface equals the saturated concentration at surface temperature). Thus, at constant temperature, the driving force for mass transfer is constant which results in a constant water flux. The energy necessary for evaporation is supplied by the drying air. As a result, the product temperature decreases to the wet bulb temperature. The ratio of the concentration difference and the temperature difference between surface and bulk air can be calculated with the psychrometric equation:

$$\frac{\rho_{a,i} - \rho_{a,b}}{T_{a,i} - T_{a,b}} = - \frac{\rho_a c_{pa}}{h_v} \left(\frac{a_{lh}}{D_a} \right)^n \quad (4)$$

After some time, the air moisture content at the surface of the wood will be lower than the corresponding saturated moisture concentration ($a_w < 1$). In this case, moisture diffusion in the wood becomes the limiting factor. This drying stage is called the falling drying rate period. Then, the wood temperature of a thin layer (with the thickness equal to the particle thickness) can be calculated with the heat balance [Sharp, 1982]:

$$\rho_{wo}(c_{wo} + c_w M) \frac{\partial T_{wo}}{\partial t} = \rho_{wo} h_v \frac{\partial M}{\partial t} + U(T_{a,b} - T_{wo}) \quad (5)$$

where the first term represents the enthalpy change of the wood, the second term is the heat loss due to moisture evaporation, and the third term gives the convective heat transfer to the wood.

The difference in water concentration between the wood interior and the wood surface causes an internal water flux, which can be described by Fick's first law of diffusion [Crank, 1983]:

$$\Phi_m = -D \nabla C \quad (6)$$

The fundamental differential equation of diffusion, which is referred to as Fick's second law of diffusion, describes the internal change of the water concentration:

$$\frac{\partial C}{\partial t} = \nabla(D \nabla C) \quad (7)$$

From equation (7), specific diffusion equations can be derived for a plane sheet, a cylinder and a sphere [Crank, 1983]. In this paper, a willow chip will be regarded as a plane sheet, a willow stem (with and without bark) will be regarded as an infinite long cylinder (length/diameter $\gg 1$). For both geometries, diffusion equations and initial and boundary conditions are presented in Table 1. In Table 1, the initial condition states a homogeneous initial moisture concentration. The first boundary condition states symmetry around the centre of the material. The second boundary condition states the mass transfer of moisture to the air: the diffusive flux at the edge ($x = \pm L$ or $r = R$) is equal to the difference in air moisture concentration at the surface of the wood $\rho_{a,i}$ and the drying air $\rho_{a,b}$, multiplied by the mass transfer coefficient k .

In the diffusion equation, all possible contributions to internal moisture transfer are lumped into one effective diffusivity D_{eff} . It was argued by Fyhr and Kemp [1998] that a moisture dependent diffusivity is required for adequate modelling of low temperature drying. Therefore, D_{eff} is described with a power law relation of the dimensionless moisture concentration m [Coumans, 1987; Lievens et al., 1990]:

$$D_{eff} = D_0 m^n \quad (8)$$

Table 1: Equations, conditions and empirical relations for the willow material.

Geometry	Willow Chip	Willow Stem
Mathematical geometry ^a :	plane sheet	cylinder
Diffusion equation ^a :	$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} (D_{\text{eff}} \frac{\partial C}{\partial x})$	$\frac{\partial C}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (r D_{\text{eff}} \frac{\partial C}{\partial r})$
Initial condition ^a :	$t = 0, -L < x < L, C_{0,x} = C_0$	$t = 0, 0 < r < R, C_{0,r} = C_0$
1 st Boundary condition ^a :	$t > 0, x = 0, \frac{\partial C}{\partial x} = 0$	$t > 0, r = 0, \frac{\partial C}{\partial r} = 0$
2 nd Boundary condition ^a :	$t > 0, x = \pm L, -D_{\text{eff}} \frac{\partial C_{i,L}}{\partial x} = k(\rho_{a,i} - \rho_{a,b})$	$t > 0, r = R, -D_{\text{eff}} \frac{\partial C_{i,R}}{\partial r} = k(\rho_{a,i} - \rho_{a,b})$ ^c
Empirical relation ^b :	$Nu = 0.332 Re^{0.5} Pr^{0.33}$	$Nu = (0.4 Re^{0.5} + 0.06 Re^{0.667}) Pr^{0.4}$
Validity range of dim. numbers ^b :	$Re : 1 * 10^5 - 5.5 * 10^6, Pr : 0.70 - 380$	$Re : 1 - 1 * 10^5, Pr : 0.67 - 300$

^a Crank, 1983

^b Whitaker, 1972

^c for willow stems with bark: $D_{\text{eff}} = D_{\text{eff,bark}}$

D_0 and a are fit parameters which are calculated from the experimental drying curve. The dimensionless moisture concentration m is defined as:

$$m = \frac{C - C_e}{C_0 - C_e} \quad (9)$$

The moisture content of the wood will finally be in equilibrium with the drying air, as the wood reaches its equilibrium moisture content (EMC). The relation between the relative humidity and EMC at constant temperature is given by the sorption isotherm.

3 Materials and methods

3.1 Willow material

Drying experiments with willow chips were conducted in 1998. Willow chips were produced from 4 years old willow stems (*Salix viminalis* L.) with a mobile chipper (Schliesing 660ZX). Two particle sizes were produced, classified as 'small' and 'large'. The dimensions of the chips were determined by taking 50 chips at random from each size. Length, width and height of the chips were measured with a calliper rule. An appropriate parameter for characterization of the bulk material is the particle size distribution which was determined by sieving [Curvers and Gigler, 1996].

Drying experiments with willow stems were conducted in 1997. Willow samples with a length of approximately 0.23 m were cut from 3 years old willow stems. Stem radii were measured at the middle of the cylinder with a calliper rule. To ensure that only radial diffusion occurs, during the drying process, both ends of the cylinders were sealed airtight with tape. For the drying experiments with willow stems without bark, the bark of the stems was removed with a knife. Moisture contents were determined from the weight loss of samples dried in a drying cabinet at 105 °C during 72 hours [ASAE Standard, 1994].

3.2 Sorption isotherm

The sorption isotherm of willow was determined by drying wood samples at different constant relative humidities and temperatures. A constant relative humidity can be created in a closed environment with saturated salt solutions (Table 2) [Weast, 1975]. A constant temperature was created by placing small containers filled with saturated salt solutions in an insulated box with temperature-controlled water. The measurements and the drying experiments were carried out at 20 °C. Fresh wood samples were placed in the containers just above the salt solutions. During several weeks, the samples were weighed periodically until the weight change was less than 1%, which meant that the moisture content was at equilibrium.

Table 2: Relative humidity of saturated salt solutions at 20 °C [Weast, 1975] and corresponding equilibrium moisture contents (EMC) of willow.

Salt Solution	Relative Humidity %	EMC (\pm SD) kg water.(kg DM) ⁻¹
Lithium Chloride	11.3	0.04 \pm 0.01
Magnesium Chloride	33.1	0.10 \pm 0.03
Potassium Carbonate	43.2	0.10 \pm 0.01
Sodium Chloride	75.5	0.19 \pm 0.01
Ammonium Sulphate	81.0	0.20 \pm 0.03
Potassium Hydro Sulphate	85.6	0.23 \pm 0.01
Strontium Nitrate	86.9	0.23 \pm 0.01
Zinc Sulphate	89.7	0.26 \pm 0.01
Sodium Sulphate	92.5	0.71 \pm 0.01
Potassium Nitrate	94.0	0.35 \pm 0.01
Potassium Sulphate	97.6	1.33 \pm 0.02
Copper(II)Sulphate	97.7	1.41 \pm 0.10

The water sorption isotherm was based on the Modified-Halsey equation for constant temperature [Chen and Vance Morey, 1989]:

$$a_w = \exp(\beta_1 M^{\beta_2}) \quad \text{for } M > 0 \quad (10)$$

where a_w is the water activity and M the moisture content. The Modified-Halsey equation contains two fit parameters (β_1 and β_2) which were determined with a least squares fitting procedure (leastsq) in MATLAB [The MathWorks, 1999].

3.3 Drying equipment

The drying equipment consisted of 24 baskets (length x width: 0.3 x 0.2 m²) with a perforated bottom, through which air with constant temperature and relative humidity was forced from below. Each basket was placed on a load sensor (maximum load 2 kg, accuracy 0.1%). Drying experiments were carried out with a relative humidity of 60% and a temperature of 20 °C. At pre-set times, the weight of the baskets was measured automatically.

For willow chips of each size class, the bottom of four baskets was covered with one layer of chips. For willow stems, each basket contained three to six samples of approximately the same radius. Measurements were done with multiple particles (instead of one) to ensure enough mass per basket, in order to minimize the influence of the measurement error of the load sensor on the experimental drying

curves. Due to the long duration (three months) of the drying experiments with willow stems, several problems occurred: mould growth, resprouting and an electricity supply failure. As a result, drying data of one week were lost but the results (Figure 4 and 5) show that this loss did not influence the experimental drying curves.

The superficial air velocity in the baskets of the drying installation was measured with air speed sensors to check the order of magnitude. The sensors (hot wire anemometer, Schmidt SS20.011) were calibrated in the range 0.15-17.0 m.s⁻¹. The sensors were placed 2 cm above the chips. Measurements were only carried out for chips.

3.4 Mathematical solutions of the drying equations

The diffusion equations of the chip and stems were solved numerically by discretization with the finite difference method of Crank-Nicolson [Von Rosenberg, 1977]. The particle was divided into $n-1$ homogenous layers. The diffusivity D_{eff} in each layer was assumed to be a power law function of the moisture content [see equation (8)]. Temperature dependence of the diffusivity was not incorporated because the model was only intended for low temperature drying, at which temperature differences, and thus the effect on the diffusivity, are low [Koponen, 1985]. The drying simulation models were designed in MATLAB. Temperature, relative humidity and drying air velocity, together with the material characteristics (effective diffusivity, initial moisture content, willow material dimensions), served as input parameters. The output parameter was the wood moisture content as a function of time.

The following procedure was used to fit the drying model (diffusion equation inclusive heat balance) to the experimental data of the willow chip and the stem without bark:

1. The air velocity v was used to fit visually the drying model to the experimental data during the constant drying rate period. The reason for fitting v visually in the constant rate period is that the experimental and the simulated drying curve should have the same slope in the constant rate period, rather than minimum differences (R^2_{adj} , which is the fraction of variance accounted for, was not determined).
2. With the air velocity v fixed, the drying model was fitted to the complete experimental drying curve using D_0 and a as fit parameters. For different combinations of D_0 and a , R^2_{adj} was determined and the combination with the highest R^2_{adj} was selected.

For the willow stem with bark, the outer layer (the bark) had a much smaller diffusivity $D_{eff,bark}$ than the inner layers. $D_{eff,bark}$ was also assumed to be a power law function of the moisture content. The drying model for the willow stem with bark was

fitted to the experimental data by using D_{bark} and a_{bark} as fit parameters. For the inner part of the stem, D_0 and a were used which were determined for the willow stem without bark. The air velocity v was not used in the fitting procedure because the bark diffusivity limits the drying process. For all willow stem with bark, the thickness of the $n-1$ layers was kept constant while the number of layers was variable.

4 Results and discussion

4.1 Willow material

The diffusion distance, defined as half the smallest dimension, was $1.0 \cdot 10^{-3}$ m and $2.5 \cdot 10^{-3}$ m, respectively, for chip size classes 'small' and 'large' (Table 3).

Table 3: Dimensions ($\cdot 10^{-3}$ m \pm SD) and initial average moisture contents [kg water.(kg DM) $^{-1}$ \pm SD] of different size classes of willow chips.

Size	Length	Width	Height	Ratio (l : w : h)	MC
Small	8.3 ± 5.7	4.4 ± 2.5	2.0 ± 1.3	4.2 : 2.2 : 1	0.72 ± 0.05
Large	17.1 ± 2.3	11.0 ± 3.8	5.1 ± 1.8	3.4 : 2.2 : 1	0.78 ± 0.03

Generally, the ratio between length, width and height of the chips is 3 to 4 : 2 : 1. In Figure 1, the particle size distribution of chip size classes 'small' and 'large' is presented.

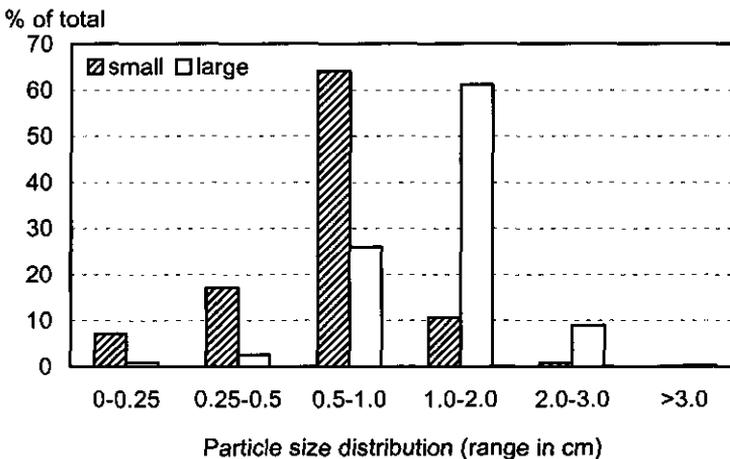


Figure 1: Particle size distribution of willow chips for size classes 'small' and 'large'.

For size class 'small', 80% of the total weight consisted of particles between 0.25 and 1 cm, and for size class 'large', 90% was between 0.5 and 2 cm. The average radii and initial moisture contents of the willow stems are presented in Table 4. The average final moisture content was $0.132 \text{ kg water} \cdot (\text{kg DM})^{-1}$. The equilibrium moisture contents (EMC) of the willow samples are presented in the last column of Table 2 for a temperature of $20 \text{ }^\circ\text{C}$. The sorption isotherm is presented in Figure 2. At constant air temperature ($T_a=20 \text{ }^\circ\text{C}$), the values of the fit parameters β_1 and β_2 were -0.017 and -1.6794 , respectively.

Table 4: Average radii and initial average moisture contents of willow stems.

Sample	Radius $\cdot 10^{-2} \text{ m} \pm \text{SD}$	MC $\text{kg water} \cdot (\text{kg DM})^{-1}$
1-willow stems without bark	1.19 ± 0.09	0.96
2 "	1.29 ± 0.05	0.98
3 "	1.47 ± 0.04	0.94
4 "	1.51 ± 0.05	0.99
5 "	1.68 ± 0.07	1.03
6 "	1.69 ± 0.01	0.97
7 "	1.83 ± 0.09	1.04
1-willow stems with bark	1.09 ± 0.07	1.11
2 "	1.19 ± 0.03	1.07
3 "	1.43 ± 0.03	1.01
4 "	1.51 ± 0.03	1.03
5 "	1.56 ± 0.02	1.02
6 "	1.63 ± 0.03	1.00
7 "	1.73 ± 0.02	1.01
8 "	1.82 ± 0.05	1.02
9 "	1.90 ± 0.05	1.03
10 "	2.05 ± 0.11	1.05

4.2 Drying experiments and simulations

The order of magnitude of the superficial air velocity v in the baskets of the drying installation was 0.1 to $0.2 \text{ m} \cdot \text{s}^{-1}$. Due to the non linearity of the equations in the drying models, the fit parameters were hard to identify. Therefore, it was difficult to determine confidence intervals with an optimization procedure [Hendrix, 1998]. Consequently, for different combinations of the fit parameters D_0 and a for chips and stems without bark, and D_{bark} and a_{bark} for stems with bark, average R^2_{adj} were

determined, based on the smallest and largest particle dimensions used in the experiments (Table 5). The fit parameters with the highest R^2_{adj} were selected for the model simulations. As a selection criterion, $R^2_{adj} \geq 0.99$ was chosen for the fit parameters of chips and stems without bark, because due to the long constant drying rate period, several combinations had a very high R^2_{adj} . The confidence intervals given hereafter are an approximation based on Table 5.

Moisture Content (kg water/kg DM)

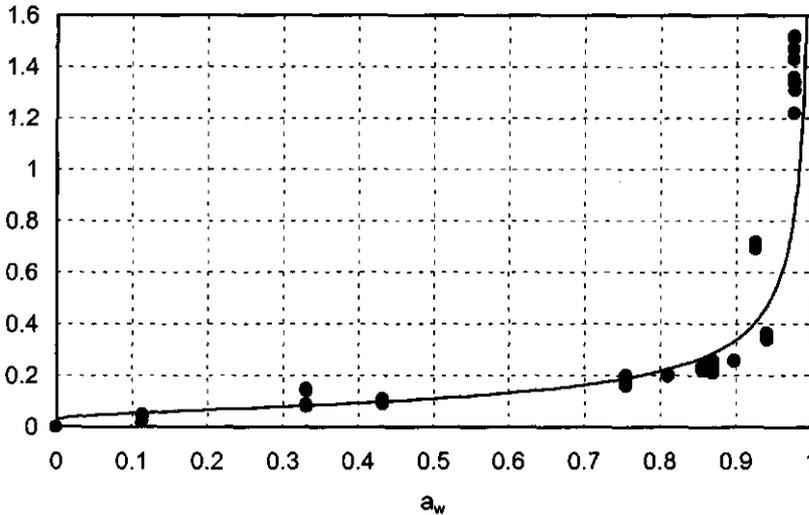


Figure 2: Sorption isotherm of willow at 20 °C (• = experimental data, – = fitted line according to the Modified-Halsey equation; $R^2_{adj} = 0.70$).

Willow chips: Figure 3 shows the experimental and simulated drying curves for willow chips (note: time axis in 10^5 s). Chip size 'small' dried much faster than 'large' due to the smaller diffusion distance. The diffusion equation for a plane sheet described willow chip drying very well. The fitted values for the power law diffusion were $D_0 = (3.0 \pm 1.0) \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ and $a = 0.3 \pm 0.1$. The air velocity used in the drying simulations was $0.16 \text{ m} \cdot \text{s}^{-1}$. The arrows in Figure 3 indicate when the constant drying rate ends, according to the simulated drying curve. Drying of chip size 'large' was simulated with the average dimensions given in Table 3. For chip size 'small', a chip thickness (height) of $3.1 \cdot 10^{-3} \text{ m}$ was selected, because simulated drying times with the average thickness were too short. However, the selected thickness was well within the range indicated.

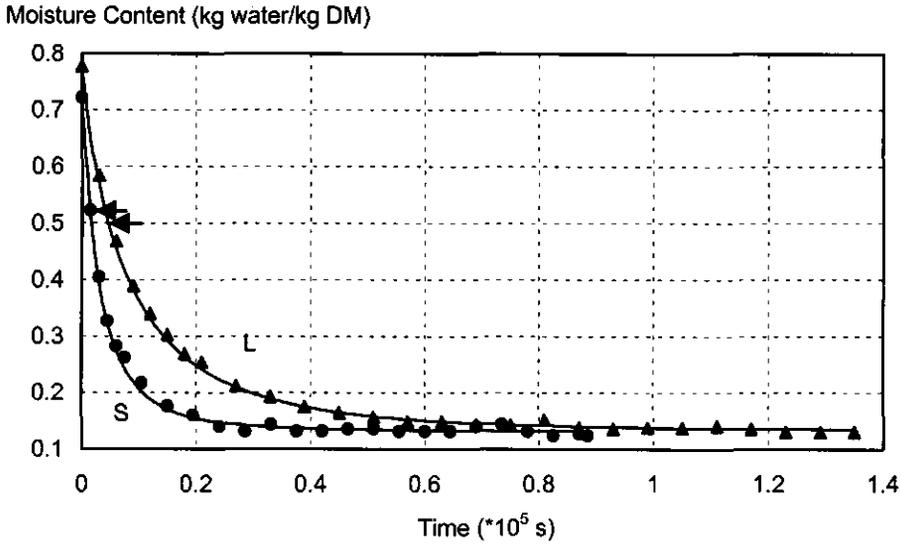


Figure 3: Simulated (—) versus experimental (●, ▲) drying curves for chips (small S; large L) ($R^2_{adj} = 0.996$); arrows indicate the end of the constant drying rate period.

Willow stems without bark: Figure 4 shows the experimental and simulated drying curves for willow stems without bark for the smallest and largest stem radii (note: time axis in 10^6 s). The diffusion equation for a cylinder adequately described stem drying. The fitted values for the power law diffusion were identical to those for chips: $D_0 = (3.0 \pm 1.0) \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ and $a = 0.3 \pm 0.2$. The air velocity used in the simulations was $0.14 \text{ m} \cdot \text{s}^{-1}$. The drying rates of the willow stems became smaller with increasing stem diameter due to an increase of the diffusion distance. Between $0.4 \cdot 10^6 - 0.6 \cdot 10^6$ s, data are missing due to data acquisition problems (indicated in section 3.3).

Willow stems with bark: Figure 5 shows the experimental and simulated drying curves for willow stems with bark (note: time axis in 10^7 s). The system of a diffusion equation for a cylinder, surrounded by a layer with a much lower diffusivity (bark), adequately described stem drying. The fitted values for the power law diffusion of the bark were $D_{bark} = (2.25 \pm 0.25) \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ and $a_{bark} = -0.4 \pm 0.1$. The drying time increases with stem diameter due to a larger diffusion distance. Figure 5 also shows that the drying experiment was terminated too early, because the stems with bark with $R = 0.0205 \text{ m}$ had not reached EMC at the end of the experiment. Around $0.1 \cdot 10^7$ s, data are missing due to data acquisition problems (indicated in section 3.3).

In Figure 3, 4 and 5, chips show the fastest drying rates because they have a smaller diffusion distance than stems (without bark). Willow stems with bark dried approximately 10 times slower than stems without bark, from fresh state to EMC,

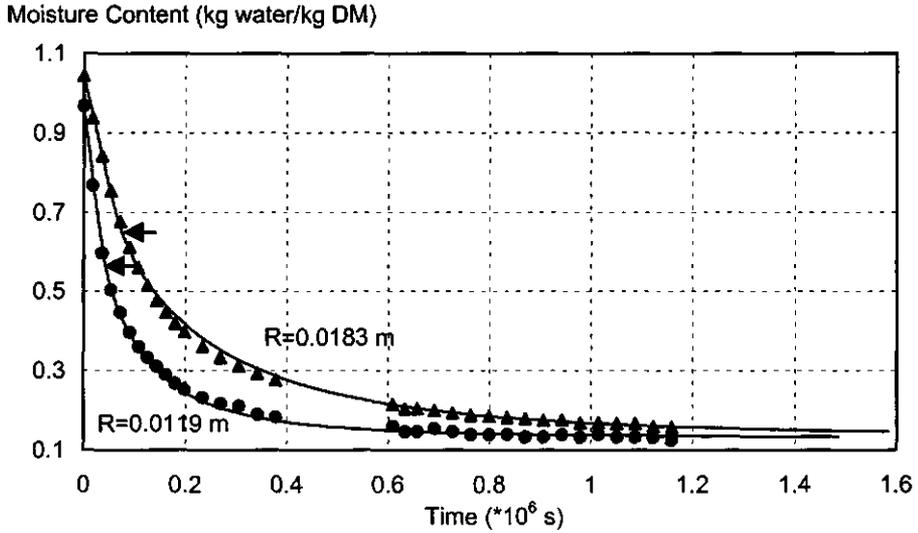


Figure 4: Simulated (—) versus experimental (●, ▲) drying curves for willow stems without bark for two radii ($R^2_{adj} = 0.997$); arrows indicate the end of the constant drying rate period.

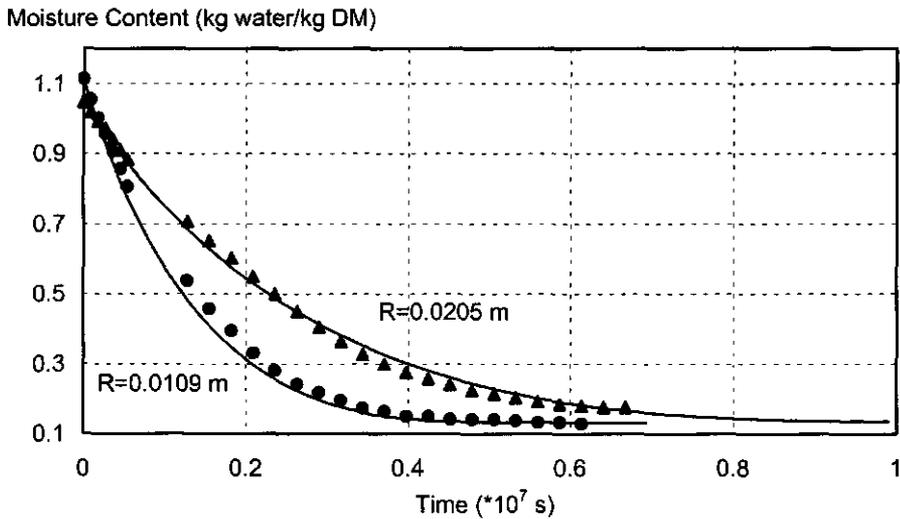


Figure 5: Simulated (—) versus experimental (●, ▲) drying curves for willow stems with bark for two radii ($R^2_{adj} = 0.993$).

due to the low bark diffusivity. The order of magnitude of the wood diffusivity D_0 is $10^{10} \text{ m}^2 \cdot \text{s}^{-1}$ which is in accordance with literature values [Koponen, 1984; Kayihan and Stanish, 1984; Siau, 1984]. The effective diffusivity D_{eff} of the chip and stem without bark decreased with moisture content ($a > 0$), which is also in accordance with literature [Siau, 1984]. The effective bark diffusivity increased with moisture content ($a_{\text{bark}} < 0$), because the resistance to water transport of the stem decreased. During visual inspection after termination of the drying experiment, cracks were observed in the bark, and the bark had become loose from the rest of the stem at several places, which may explain the reduced resistance of the bark to water transport at low moisture contents. Also bark shrinkage was observed; indicative measurements showed that the bark shrank approximately 40% from fresh to oven dry state.

Table 5: Fraction variance accounted for, for different combinations of the fit parameters D_0 and a for chips (top), stems without bark (centre), and stems with bark (bottom) (bold: combinations according to selection criterion $R^2_{\text{adj}} \geq 0.99$; underlined: combinations selected for model simulation).

Chips						
$D_0 * 10^{10} \downarrow$	$a \rightarrow 0$	0.1	0.2	0.3	0.4	0.5
1	0.816	0.690	0.527	0.320	-	-
2	0.988	0.996	0.987	0.950	0.887	0.798
3	0.925	0.958	0.983	<u>0.996</u>	0.994	0.972
4	-	0.906	0.938	0.966	0.985	0.956

Stems without bark								
$D_0 * 10^{10} \downarrow$	$a \rightarrow 0$	0.1	0.2	0.3	0.4	0.5	0.6	0.7
1	0.798	0.668	0.499	-	-	-	-	-
2	0.988	0.990	0.971	0.929	0.859	-	-	-
3	0.938	0.968	0.989	<u>0.997</u>	0.987	0.957	0.906	-
4	-	0.922	0.953	0.978	0.993	0.994	0.980	0.948
5	-	-	0.915	0.946	0.972	0.988	0.993	0.983
6	-	-	-	-	0.946	0.969	0.985	0.989

Stems with bark						
$D_{\text{bark}} * 10^{12} \downarrow$	$a_{\text{bark}} \rightarrow -0.2$	-0.3	-0.4	-0.5	-0.6	-0.7
1.75	-	0.895	0.930	0.957	0.977	0.986
2	0.939	0.964	0.982	0.992	0.992	0.981
2.25	0.978	0.990	<u>0.993</u>	0.987	0.971	-
2.5	0.989	0.988	0.978	0.959	-	-

5 Conclusions

The following conclusions are drawn:

1. Drying of a willow chip and a stem without bark could be successfully described with a diffusion equation for a plane sheet and a cylinder, respectively.
2. Drying of a willow stem with bark could be successfully described as drying of a system consisting of a willow stem without bark, surrounded by a small layer (bark) with a much lower diffusivity.
3. The effective diffusivities of the willow wood and the bark can be described with a power law relation of the dimensionless moisture concentration. For a willow chip and a willow stem without bark, the values of the fit parameters were identical: $D_0=(3.0\pm 1.0)\cdot 10^{-10} \text{ m}^2\cdot\text{s}^{-1}$ and $a=0.3\pm 0.1$ and 0.3 ± 0.2 , respectively. The power law coefficient a was positive because the effective diffusivity decreased with decreasing moisture content. For the willow stem with bark, the fit parameters of the bark were $D_{bark}=(2.25\pm 0.25)\cdot 10^{-12} \text{ m}^2\cdot\text{s}^{-1}$ and $a_{bark}= -0.4\pm 0.1$, while the parameters of the inner part of the stem were equal to chips and stems without bark. Power law coefficient a_{bark} was negative because the effective bark diffusivity increased with a decreasing moisture content, due to a reduced resistance of the bark to water transport, and bark shrinkage.
4. A willow stem without bark dried approximately 10 times slower than a willow chip from fresh state to EMC, mainly due to the larger diffusion distance. A stem with bark dried approximately 10 times slower than a stem without bark, from fresh state to EMC, mainly due to the lower bark diffusivity.

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Notation

a	power law fit parameter for diffusivity, -
a_{bark}	power law fit parameter for diffusivity, -
a_{th}	thermal diffusivity, $\text{m}^2\cdot\text{s}^{-1}$
a_w	water activity, -
c_{pa}	specific heat of air, $\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$
c_w	specific heat of water, $\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$
c_{wo}	specific heat of wood, $\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$
C	water concentration, $\text{kg}\cdot\text{m}^{-3}$
C_e	equilibrium water concentration of wood, $\text{kg}\cdot\text{m}^{-3}$
$C_{t,L}$	water concentration at the surface of the wood chip, $\text{kg}\cdot\text{m}^{-3}$

$C_{t,R}$	water concentration at the surface of the wood cylinder, kg.m^{-3}
C_0	initial water concentration, kg.m^{-3}
$C_{0,r}$	initial water concentration at a radial coordinate, kg.m^{-3}
$C_{0,x}$	initial water concentration at a space coordinate, kg.m^{-3}
D	diffusivity of water in wood, $\text{m}^2.\text{s}^{-1}$
D_a	diffusivity of water in air, $\text{m}^2.\text{s}^{-1}$
D_{bark}	initial bark diffusivity, $\text{m}^2.\text{s}^{-1}$
D_{eff}	effective diffusivity of wood, $\text{m}^2.\text{s}^{-1}$
$D_{eff,bark}$	effective bark diffusivity, $\text{m}^2.\text{s}^{-1}$
D_0	initial diffusivity of water in wood, $\text{m}^2.\text{s}^{-1}$
h_v	heat of desorption of water, J.kg^{-1}
k	mass transfer coefficient, m.s^{-1}
L	half the smallest dimension, m
m	dimensionless moisture concentration, -
M	water concentration of wood, $\text{kg water}.\text{(kg DM)}^{-1}$
n	geometry parameter, -
r	radial space coordinate, m
R	radius, m
R^2_{adj}	fraction of variance accounted for
t	time, s
$T_{a,b}$	air temperature, K
$T_{a,i}$	air temperature at the wood surface i, K
T_{wo}	temperature of wood, K
U	overall heat transfer coefficient, $\text{W.m}^{-2}\text{K}^{-1}$
v	superficial air velocity, m.s^{-1}
x	space coordinate, m
X	characteristic dimension (chips: L, stems: 2R), m
α	heat transfer coefficient, $\text{W.m}^{-2}\text{K}^{-1}$
$\beta_1, \beta_2, \beta_3$	fit parameters, -
λ	thermal conductivity, $\text{W.m}^{-1}\text{K}^{-1}$
μ	dynamic viscosity, $\text{kg.m}^{-1}\text{s}^{-1}$
$\rho_{a,i}$	water concentration of air at the wood surface i, kg.m^{-3}
$\rho_{a,b}$	water concentration of air in the bulk, kg.m^{-3}
ρ_a	air density, kg.m^{-3}
ρ_{wo}	wood density, (kg DM).m^{-3}
Φ_m	mass flux, $\text{kg.m}^{-2}\text{s}^{-1}$
Φ_q	heat flux, $\text{J.m}^{-2}\text{s}^{-1}$

$$Nu = \frac{\alpha X}{\lambda} \quad \text{Nusselt number, -}$$

$$Re = \frac{v \rho_a X}{\mu} \quad \text{Reynolds number, -}$$

$$Pr = \frac{\mu C_{pB}}{\lambda} \quad \text{Prandtl number, -}$$

4

Forced convective drying of willow chips

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Abstract

The forced convective drying process of willow chips was described with a deep bed drying model. The model consisted of four partial differential equations which describe the water and heat balances of both willow chip bed and drying air. The model was validated experimentally for bed moisture content, air temperature and relative humidity. The model adequately described ambient air drying of a 1 m willow chip bed. At the top layers of the chip bed, the drying rate was overestimated due to vapour condensation which was not incorporated into the model. However, the drying model was an appropriate tool to gain insight into the forced convective drying process of willow chips. The drying costs of willow chips using farm facilities for storage and drying of potatoes were assessed, based on average monthly weather data. March to September was the most suitable period for drying due to favourable ambient weather conditions. In this period, energy costs for drying from a moisture content of 1 to 0.18 kg water.(kg DM)⁻¹ ranged from 12 to 25 EURO.(t DM)⁻¹, or from 28 to 59 EURO.(t DM)⁻¹ when investment costs were partly accommodated.

1 Introduction

Replacing fossil fuels by biomass reduces CO₂ emissions. In this perspective, willow (*Salix viminalis*) short rotation coppice gains increasing interest as biomass fuel. Besides, growing willow can be an additional source of income for farmers. At harvest, the moisture content of willow is approximately 1 kg water.(kg DM)⁻¹. If willow is harvested as chips, which is a common harvest technique, drying can be advantageous because:

- a lower moisture content enables long term bulk storage of willow chips with low microbial activity, and thus low DM-losses and reduced health risks [Gjölsjö, 1988; Mitchell et al., 1988; Jirjis, 1995a];
- a lower moisture content increases conversion efficiency of willow into electricity and reduces gaseous emissions [Lyons et al., 1989; Van den Broek et al., 1995].

To reduce the moisture content of willow chips, farm facilities for potato storage and drying may be used during periods that these facilities are not used for potatoes. These facilities have a large capacity, are easily accessible, and equipment for handling and drying of potatoes can be used for chips. Using farm facilities for willow chip drying can be economically interesting because multiple use means that the fixed costs of facilities and equipment can be shared by different products, and thus increase the overall profitability for the farmer [Gigler et al., 1999a]. However, it is not known to which extent the ventilation equipment for potatoes is suited for willow chip drying. To evaluate the use of farm facilities for potatoes and the associated costs, drying and pressure drop characteristics of willow chips, and average fan characteristics should be combined.

The drying process of a product can be predicted with appropriate drying models, given product mass, product drying characteristics and drying air conditions. During a drying process, two periods can be distinguished [Strumillo and Kudra, 1986]. In the first so-called constant drying rate period, mainly water attached to the product superficially is evaporated. In the second so-called falling drying rate period, internal diffusion of water to the surface of the product takes place.

To describe the drying process in a product bed, different types of models exist [Sharp, 1982; Parry, 1985; Kamke and Vanek, 1992; Kiranoudis et al., 1992; Cenkowski et al., 1993]. Of these models, partial differential equation models (PDE models) have a good physical basis. Nellist [1997b] described the drying process of willow chips with a PDE model but the water balance of chips was described with an empirical relation (Page's equation). Nellist validated the deep bed model experimentally at different constant air temperatures, for chip bed temperature and moisture content. The disadvantage of an empirical drying equation is that many drying experiments at different air conditions are necessary to describe the drying characteristics at different external conditions. If the water balance is based on physical parameters, e.g. a diffusion model, the effect of different external conditions can more easily be accommodated [Gigler et al., 1999b].

The main objectives of the current study are:

1. to provide a deep bed drying model for willow chips, suited for varying drying air conditions, which is calibrated with experimental data;
2. to assess the technical possibilities and the associated costs of drying willow chips with farm facilities for potatoes.

2 Theory

2.1 Deep bed drying model

For deep bed drying, PDE models have been described extensively for grain [Spencer, 1969; Ingram, 1976; Sharp, 1982; Laws and Parry, 1983; Parry, 1985; Sun et al., 1995]. A PDE model contains four coupled balance equations describing water and energy balances of both product and drying air. Moisture and temperature gradients in product and air are accounted for. The main assumptions of the deep bed models are [Sun et al., 1995]:

- shrinkage during drying is negligible;
- uniform packing density of the product bed;
- heat conduction in the bed is negligible;
- uniform air flow through the bed (plug type);
- temperature gradients within individual particles are negligible;

- heat capacities are constant;
- evaporating water extracts heat of desorption from the product and enters the air stream as water vapour at product temperature.

For willow chips, a detailed explanation of a deep bed drying PDE model is given hereafter. The water balance of the drying air is based on the assumption that the water gradient is caused by evaporation of water from the wood:

$$v\rho_a \frac{\partial H}{\partial X} = -\rho_{wo} \frac{\partial M}{\partial t} \quad (1)$$

The energy balance of the air describes the change of the enthalpy of the air, which is equal to the heat loss by heating of the evaporated water from wood to air temperature, and the heat transfer from air to wood:

$$v\rho_a(c_{pa} + c_v H) \frac{\partial T_a}{\partial X} = \rho_{wo} c_v (T_a - T_{wo}) \frac{\partial M}{\partial t} - U(T_a - T_{wo}) \quad (2)$$

Equations (1-2) are steady state balances: the storage terms involving $\partial H/\partial t$ in equation (1) and $\partial T_a/\partial t$ in equation (2) are not taken into account because, quantitatively, their contributions to the equations are negligible [Ingram, 1976]. The energy balance of the wood states that the change of the enthalpy of the wood is equal to the heat needed for evaporation and the heat transfer from the air to the wood:

$$\rho_{wo}(c_{wo} + c_w M) \frac{\partial T_{wo}}{\partial t} = \rho_{wo} h_v \frac{\partial M}{\partial t} + U(T_a - T_{wo}) \quad (3)$$

In our approach, the water lost in the willow chip bed in equation (1-3), $\partial M/\partial t$, is the water transferred from the chip surface to the air. This water has to diffuse from the interior of the chip to the surface, as represented by a diffusion model for a plane sheet [Crank, 1983; Gigler et al., 1999b]:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D_{\text{eff}} \frac{\partial C}{\partial x} \right) \quad (4)$$

The average chip moisture concentration C_{av} is equal to $\rho_{wo} \cdot M$. One initial and two boundary conditions are necessary to fully describe the internal diffusion process in the chip. The initial condition states a homogeneous initial moisture concentration. The first boundary condition states symmetry around the centre of the chip. The second boundary condition describes the mass transfer of moisture to the air: the diffusive flux at the edge ($x=\pm L$) is equal to the difference in air moisture concentration at the surface of the wood $\rho_{a,i}$ and in the drying air $\rho_{a,b}$, multiplied by the mass transfer coefficient k :

$$t > 0, \quad x = \pm L, \quad -D_{eff} \frac{\partial C_{t,L}}{\partial x} = k(\rho_{a,i} - \rho_{a,b}) \quad (5)$$

All possible contributions to internal moisture transfer are lumped into one effective diffusivity D_{eff} for the chip, which is described with a power law relation of the dimensionless moisture concentration m [Coumans, 1987; Lievens et al., 1990]:

$$D_{eff} = D_0 m^a \quad (6)$$

where D_0 and a are fit parameters. The heat transfer coefficient α can be calculated with an empirical relation for $Nu = f(Re, Pr)$ for a packed bed [Whitaker, 1972]:

$$Nu = (0.5 Re^{0.5} + 0.2 Re^{0.67}) Pr^{0.33} \quad (7)$$

The mass transfer coefficient k can be calculated from α according to:

$$\frac{\alpha}{k} = \rho_a C_{pa} \left(\frac{a_m}{D_a} \right)^{0.67} \quad (8)$$

The water sorption isotherm describes the water activity a_w at the surface of the wood which is in equilibrium with the relative humidity of the air. The water sorption isotherm was based on the Modified-Halsey equation for constant temperature [Chen and Vance Morey, 1989]:

$$a_w = \exp(\beta_1 M^{\beta_2}) \quad \text{for } M > 0 \quad (9)$$

At constant air temperature ($T_a=20$ °C), β_1 and β_2 are -0.017 and -1.6794 , respectively.

2.2 Pressure drop characteristics

During forced drying, the air pressure drop over a product bed determines the volume flow of air through the bed for a given fan. For laminar airflows ($Re < 3$), the pressure drop is a linear function of the superficial air velocity (Darcy's law). For fully turbulent airflow ($Re > 600$), this relation is quadratic. For near laminar flows ($3 < Re < 600$), the relation contains both a linear and a quadratic velocity term [Bear and Corapcioglu, 1984]. Here, an empirical relation is used:

$$\Delta P = h k_1 v^{k_2} \quad (10)$$

where k_1 and k_2 are fit parameters which depend on size and shape of the willow chips. The fit parameters can be determined from experimental data. Gustafsson [1988], Kofman and Spinelli [1997] and Nellist [1997b] derived values of the fit parameters of equation (10) for wood chips. In the size range 10-25 mm, the average values of the fit parameters are $k_1=1,755$ and $k_2=1.67$. When the

characteristics of drying and pressure drop in the product, and the drying air conditions are known, for a given fan the drying time can be determined (section 3).

3 Materials and methods

3.1 Willow material

For the thin layer and deep bed drying experiments, different batches of chips were produced from 4 years old willow stems (*Salix viminalis* L.). The particle size distribution of the chips was determined by sieving [Curvers and Gigler, 1996]. Chip dimensions were measured with a calliper-square for 50 chips taken at random from the two predominant sieving fractions. The moisture content was determined by drying at 105 °C for 72 hours [ASAE, 1994]. Chip size, diffusion distance (defined as half the smallest chip dimension) and particle size distribution of the thin layer and deep bed drying experiments were in the same order of magnitude (Table 1), but on average, the chips of the thin layer drying experiments were slightly larger. The values of the fit parameters of equation (6) were determined as $D_0=(3.0\pm 1.0)\cdot 10^{-10}$ m².s⁻¹ and $a=0.3\pm 0.1$ [Gigler et al., 1999b].

3.2 Drying equipment

Thin layer drying experiments: The drying equipment consisted of a series of baskets with perforated bottoms. From below, drying air with constant relative humidity (60%) and temperature (20 °C) was blown through the baskets, filled with willow chips. The superficial air velocity varied from 0.1 to 0.2 m.s⁻¹. The baskets were weighed continuously on load sensors which sampled automatically at pre-set times [Gigler et al., 1999b]. Four baskets contained a chip layer of 1 cm and four baskets contained a layer of 8 cm. The drying curves of the 1 and 8 cm layers were determined by taking the average of four repetitions.

Table 1: Characteristics of the willow chips.

Characteristics	Thin layer	Deep bed
Length, 10 ⁻³ m	17.1 ± 2.3	13.3 ± 7.1
Width, 10 ⁻³ m	11.0 ± 3.8	8.8 ± 4.2
Height, 10 ⁻³ m	5.1 ± 1.8	4.5 ± 2.2
Diffusion distance L , 10 ⁻³ m	2.6 ± 0.9	2.3 ± 1.1
Equivalent particle diameter D_p , 10 ⁻³ m	8.7	7.3
Initial moisture content, kg water.(kg DM) ⁻¹	0.78 ± 0.03	0.75 ± 0.02
Particle size distribution ^a	> 80%	> 80%

^a % of total weight in the range 0.5-2.0 cm

Deep bed drying experiment: The deep bed drying equipment consisted of four commonly used potato boxes with dimensions $1.05 \times 1.35 \times 1 \text{ m}^3$ ($l \times w \times h$) which had closed side walls and perforated bottoms. The bottom of each box had an open pallet-like construction which enabled a draught of drying air through several boxes in a row simultaneously (see Figure 1). The boxes were put on a rectangular metal frame which was supported by four load sensors with a range of 1,000 kg (HBM, 10 kN). The boxes were filled with willow chips, and ambient air was forced through by a fan. The following data were recorded every 600 s (data logger: Datalogger DT500):

- total weight of the boxes (load sensor);
- temperature (PT100 sensor) and relative humidity (Rotronic sensor) of incoming ambient drying air;
- temperature and relative humidity (Rotronic sensor) of the air in the box closest to the incoming air at a height of 0.2, 0.4, 0.6, 0.8 and 1 m;
- mean temperature at the centre of all boxes (thermocouples);
- superficial velocity of the air (hot wire anemometer Schmidt SS20.011), approximately 10 cm above the top chip layer.

Before and after drying, samples were taken to determine the average initial and final moisture content. The moisture content as a function of time was calculated from the weight loss during drying. The experiment started at March 20, 1998, 3 PM.

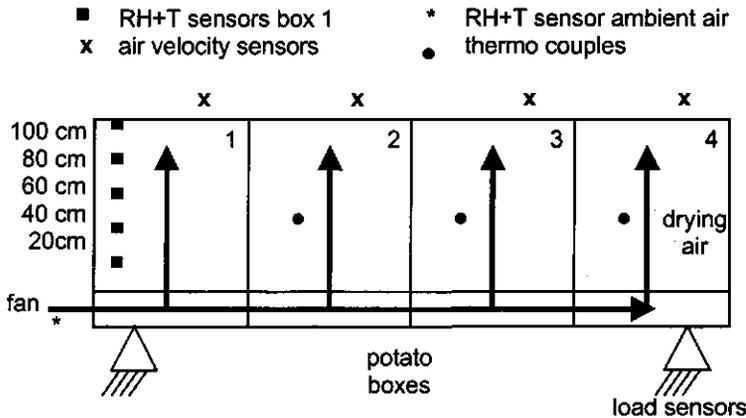


Figure 1: Side view of the large scale drying equipment.

3.3 Mathematical solutions of the drying equations

The diffusion equation was solved numerically by discretization with the finite difference method of Crank-Nicolson. The deep bed drying model was solved with an Euler forward finite difference method. The product bed was assumed to be

divided into several thin layers. The outlet conditions of one layer were used as the inlet conditions of the layer above. Each layer was assumed to be uniform in moisture content and temperature [Sharp, 1982]. Drying models were programmed in MATLAB [The MathWorks, 1999]. Input parameters were temperature, relative humidity and velocity of the drying air and the material characteristics (diffusivity, chip dimensions, initial bed moisture content and temperature). Output parameters were moisture content and temperature of the chip layers, and temperature and relative humidity of the drying air.

The deep bed drying model was calibrated on the experimental data with the following fit parameters:

- air velocity v in the bed, because the superficial velocity of the air was measured but not as precise as required;
- bed heat transfer coefficient $U = \alpha^* A_{sp}$: α was approximated with a Nu-relation which generally has an accuracy of $\pm 25\%$; A_{sp} was calculated assuming that all chips in the bed fully contributed to the specific surface area, but in reality A_{sp} will be smaller due to mutual overlap [Glaser and Thodos, 1958; Whitaker, 1972];
- chip size L , to comply with the range of the measured average chip size.

The 1 cm chip layer was used to calibrate the deep bed model on the experimental data. The following procedure was adopted:

1. By varying air velocity v and bed heat transfer coefficient $\alpha^* A_{sp}$, the deep bed drying model was calibrated on the experimental data during the constant drying rate period to fit the slope of the drying curve. External conditions limit the drying process in the constant drying rate period. The fraction of variance accounted for, R^2_{adj} , was determined for different combinations of v and $\alpha^* A_{sp}$.
2. With v and $\alpha^* A_{sp}$ fixed, chip thickness L was used to calibrate the drying model on the experimental data during the falling drying rate period. In this period, the material characteristics limit the drying process.

Step 1 and 2 were repeated with the new fitted value for L until the optimal combination was found. For the 8 cm chip bed, the values of chip thickness L and $\alpha^* A_{sp}$ from the fit procedure for a 1 cm bed were used. Only air velocity v was varied to fit the model on the experimental drying data, because the measured velocity of the air in the drying equipment varied between 0.1 and 0.2 $\text{m}\cdot\text{s}^{-1}$. The final values of the fit parameters for the model simulations were selected by estimating the median from the values matching the criterion $R^2_{adj} \geq 0.995$. This criterion was used to limit the range of valid fit parameters because these were not very sensitive to small changes.

3.4 Drying with farm facilities

Agricultural facilities for potato storage and drying differ between countries. In this paper, calculations are presented for the typical situation in the Netherlands where the average potato store is for 800 t or 1,230 m³ of potatoes, at a storage height of 3.5 m. For potato drying, axial fans are used which have reasonable plane fan characteristics (slowly decreasing pressure drop at higher airflows). Ventilation equipment is usually designed for an airflow of 100 m³ air.(m³ product. h)⁻¹ at a pressure drop of 150 Pa, with an average capacity of approximately 25,000 m³ air.h⁻¹ per fan. Generally, the pressure drop of the air distribution equipment is 100 Pa [Van Dusseldorp, 1987; Scheer, 1989].

For many agricultural and wood products, as a rule of thumb, a moisture content below 15 to 20% (wet base) or 0.18 to 0.25 kg water.(kg DM)⁻¹ is regarded as safe for long term storage, without the risk of microbial degradation [Gustafsson, 1988]. For willow, it is assumed that the initial moisture content (at harvest) is 1.0 kg water.(kg DM)⁻¹, the target moisture content after drying is 0.18 kg water.(kg DM)⁻¹ to guarantee safe storage. Based on experimental data, it was assumed that drying air leaves the chip bed always fully saturated (section 4). The following methodology was adopted to calculate the costs of forced convective drying of willow chips:

1. given the Dutch average monthly ambient RH and air temperature, the amount of water the air can take up to reach full saturation at wet bulb temperature was calculated for each month [KNMI, 1995];
2. from characteristics of an average fan (type: DLM10), the pressure drop in potatoes at different airflows was determined [IMAG, 1985];
3. for several combinations of pressure drop and airflow for potatoes, the maximum height at which willow chips can be stored in a potato store and the associated quantity of chips were determined; the pressure drop of the chips was calculated with equation (10);
4. for different chip quantities, the total volume of air necessary to evaporate all water and the drying time were calculated;
5. costs of farm facilities were determined and the share made specifically for willow was calculated [Gigler et al., 1999a];
6. from the pressure drop and the total amount of air needed, fan energy consumption was determined [Gustafsson, 1988];
7. facility and energy costs were added to determine the total costs for different chip bed heights in different months [Gigler et al., 1999a].

4 Results and discussion

4.1 Drying experiments

Thin layer drying experiments: The fitted values of the 1 cm chip bed, which were selected for model simulation from Table 2 and 3, were ($R^2_{adj} \geq 0.995$ given for completeness): $v=0.12 \pm 0.04 \text{ m.s}^{-1}$, $\alpha^*A_{sp}=0.5 \pm 0.3 \text{ W.m}^{-3}\text{K}^{-1}$ and $L=(2.8 \pm 0.1) \times 10^{-3} \text{ m}$.

Table 2: Fraction variance accounted for by different combinations of the fit parameters α^*A_{sp} and v for the 1 cm willow chip bed (bold: combinations according to selection criterion $R^2_{adj} \geq 0.995$; underlined: combination selected for model simulation).

$v \downarrow$	α^*A_{sp}								
	$\rightarrow 0.1$	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.04	-	-	-	-	0.933	0.964	0.980	0.988	0.992
0.06	-	-	-	-	0.983	0.993	0.997	0.998	0.998
0.08	-	-	-	0.984	0.996	0.998	0.998	0.998	0.997
0.10	-	-	0.970	0.994	0.998	0.998	0.997	0.996	0.996
0.12	-	-	0.985	0.998	<u>0.998</u>	0.997	0.996	0.995	0.994
0.14	-	-	0.992	0.998	0.997	0.996	0.994	0.994	-
0.16	-	0.954	0.996	0.998	0.996	0.994	0.993	-	-
0.18	-	0.968	0.998	0.997	0.995	0.993	-	-	-
0.20	-	0.978	0.998	0.997	0.994	0.993	-	-	-
0.22	-	0.985	0.998	0.996	0.993	0.992	-	-	-
0.24	-	0.989	0.998	0.995	0.993	-	-	-	-
0.26	0.802	0.993	0.998	0.994	0.992	-	-	-	-
0.28	0.827	0.995	0.997	0.994	-	-	-	-	-
0.30	0.852	0.996	0.997	0.993	-	-	-	-	-

The fitted value of α^*A_{sp} was 50% of the calculated value. This difference was due to the low accuracy of the Nu number ($\pm 25\%$), and the fact that relations for Nu numbers for packed beds are significantly lower for shapes like cubes compared to spherical objects [Whitaker, 1972]. Furthermore, the effective specific surface area in the chip bed is considerably reduced due to mutual overlap [Glaser and Thodos, 1958; Whitaker, 1972]. The fitted value of diffusion distance L was within the range presented in Table 1.

Table 3: Fraction variance accounted for by fit parameter L for the 1 cm willow chip bed (bold: combinations according to selection criterion $R^2_{adj} \geq 0.995$; underlined: combination selected for model simulation).

Fit parameter L , 10^{-3} m	2.5	2.6	2.7	2.8	2.9	3.0	3.1
R^2_{adj}	0.985	0.993	0.998	<u>0.998</u>	0.996	0.989	0.979

For the 8 cm chip layer, the fitted value for the superficial velocity of the air was $v=0.17 \text{ m}\cdot\text{s}^{-1}$ (± 0.01 , Table 4) which is about the same as the fitted values for the 1 cm chip bed. Figure 2 shows that the fit between the simulated and experimental drying curves was very good.

Table 4: Fraction variance accounted for by fit parameter v for the 8 cm willow chip bed (bold: combinations according to selection criterion $R^2_{adj} \geq 0.995$; underlined: combination selected for model simulation).

Fit parameter v , $\text{m}\cdot\text{s}^{-1}$	0.14	0.15	0.16	0.17	0.18	0.19	0.20
R^2_{adj}	0.982	0.993	0.998	<u>0.999</u>	0.998	0.994	0.989

Moisture Content (kg water/kg DM)

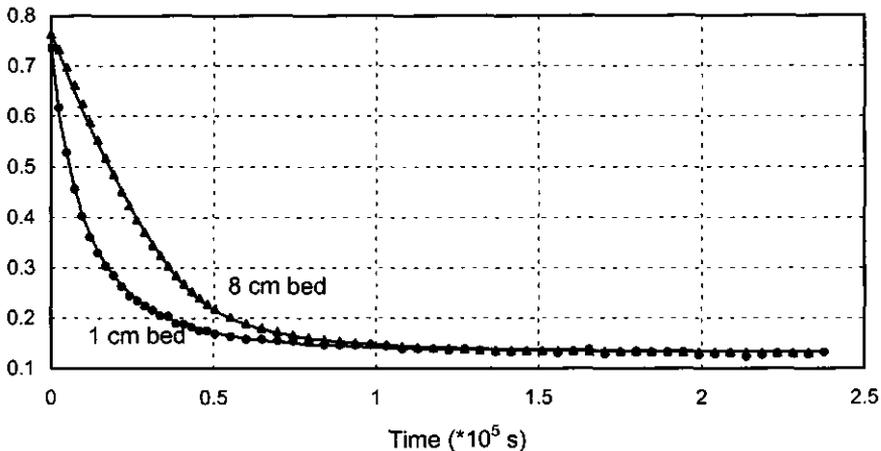


Figure 2: Simulated (—) versus experimental (\blacktriangle , \bullet) drying curves of willow chips for a chip bed of 1 and 8 cm.

Deep bed drying experiment: The total quantity of willow chips in this experiment was 1,440 kg. It was assumed that, during drying, only moisture was lost, and that the total quantity of dry matter remained constant. Figure 3 (top) shows the RH (Relative Humidity) of the ambient air (IN) and the RH in the chip box at different heights (from 0.2 to 1 m) as a function of time (h). Because the RH indicated values larger than 100%, RH-data were corrected for measurement errors by subtracting the amount above 100% from the whole dataset for each RH sensor.

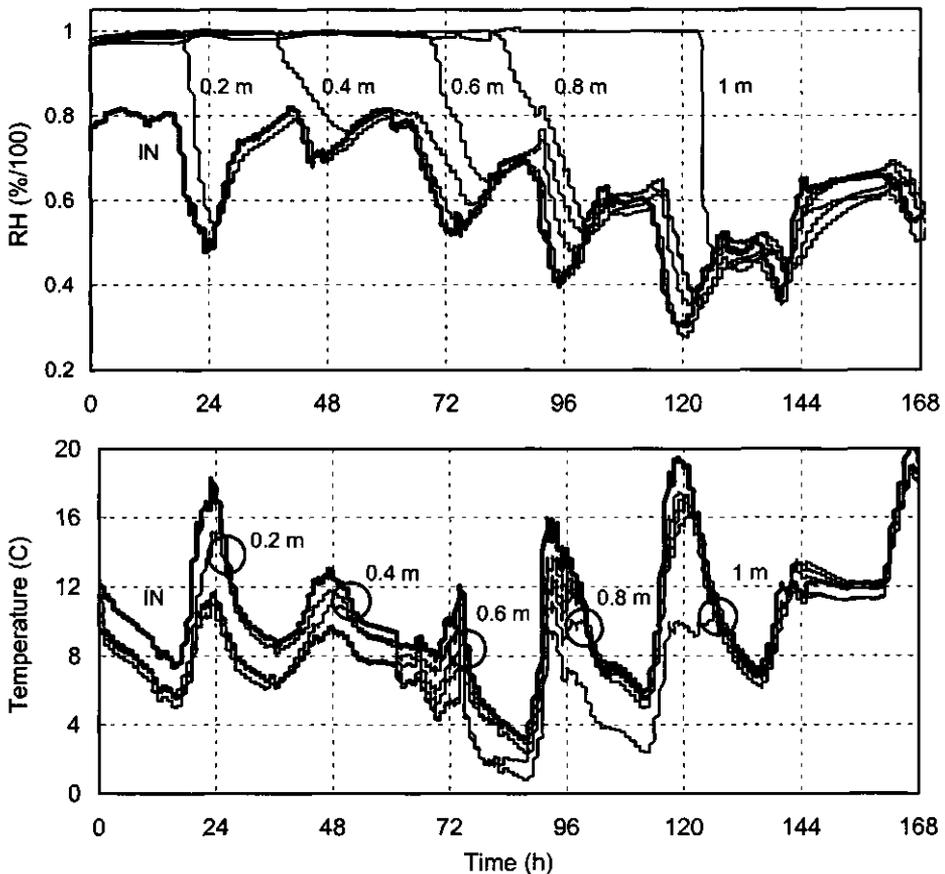


Figure 3: Measured relative humidity (top) and temperature (bottom) of the ambient air and in the 1 m chip bed at different heights (0.2, 0.4, 0.6, 0.8 and 1 m). IN represents incoming air conditions.

The drying air left the chip bed fully saturated until the equilibrium moisture content (EMC) was (nearly) reached. The progression of the drying front through the chip

bed can clearly be observed by a sharp drop of the RH to the ambient RH (for instance, Figure 3 at ca 24 h at 0.2 m), which indicates that the part of the chip bed under the sensor has (nearly) reached EMC. The willow chip bed reached its lowest moisture content after ca 124 h. The velocity of the drying front was not constant, as indicated by the varying time pattern of the drying fronts, as well as by the slope of the RH-curve when the drying front passes. This variation is due to variations of the ambient RH and temperature: at low RH (0.2 m), the drying front will move faster than at high RH (0.4 m). Between a height of 0.8 m and 1 m, the drying front slowed down despite the low RH of the ambient air which was probably caused by vapour condensation in the top layers.

Figure 3 (bottom) shows the ambient air temperature and chip bed temperature at different heights in the chip box. The air temperature rises from wet bulb to ambient air temperature (indicated by circles) after the drying front has passed, which is in accordance with the pattern of the RH graph. In Figure 3, the day-night rhythm of the RH and temperature can also be observed.

Figure 4 (top) shows the measured and simulated average moisture content of the willow chip bed as a function of time. The simulated moisture content at 124 h, $0.10 \text{ kg water} \cdot (\text{kg DM})^{-1}$, was in accordance with the measured final moisture content of $0.11 \pm 0.01 \text{ kg water} \cdot (\text{kg DM})^{-1}$. The air velocity in the chip bed, used for the simulations, was $0.55 \text{ m} \cdot \text{s}^{-1}$ which is plausible because the measured superficial air velocity was in the range of $0.3 \text{ m} \cdot \text{s}^{-1}$. The drying model adequately described the experimental drying curve except for the time interval 90-120 hrs.

In Figure 4 (middle), the simulated and measured RH is shown. At a height of 0.2, 0.4, 0.6 and 0.8 m, the drying model successfully describes the measured RH. Small differences are probably due to inaccuracies with respect to the position of the RH-sensors in the chip bed. However, at 1 m, a time delay occurs. Due to vapour condensation in the top chip layers, the drying rate is overestimated here because condensation was not incorporated into the model. Condensation can be explained as follows. The chip bed temperature will follow the ambient air temperature but with some time delay. At ca 110 h, the temperature of the ambient air rises from 5 to 19°C. Because the temperature rise in the chip bed is slower, the drying air is cooled while going through the chip bed. In the top layers, the drying air will meet the colder part of the bed, which is the last part to be heated by the air, and consequently, condensation will occur. This phenomenon occurs especially around 110 h because then the temperature difference is large (14°C). However, even without incorporation of condensation into the drying model, the model predicted the drying process adequately.

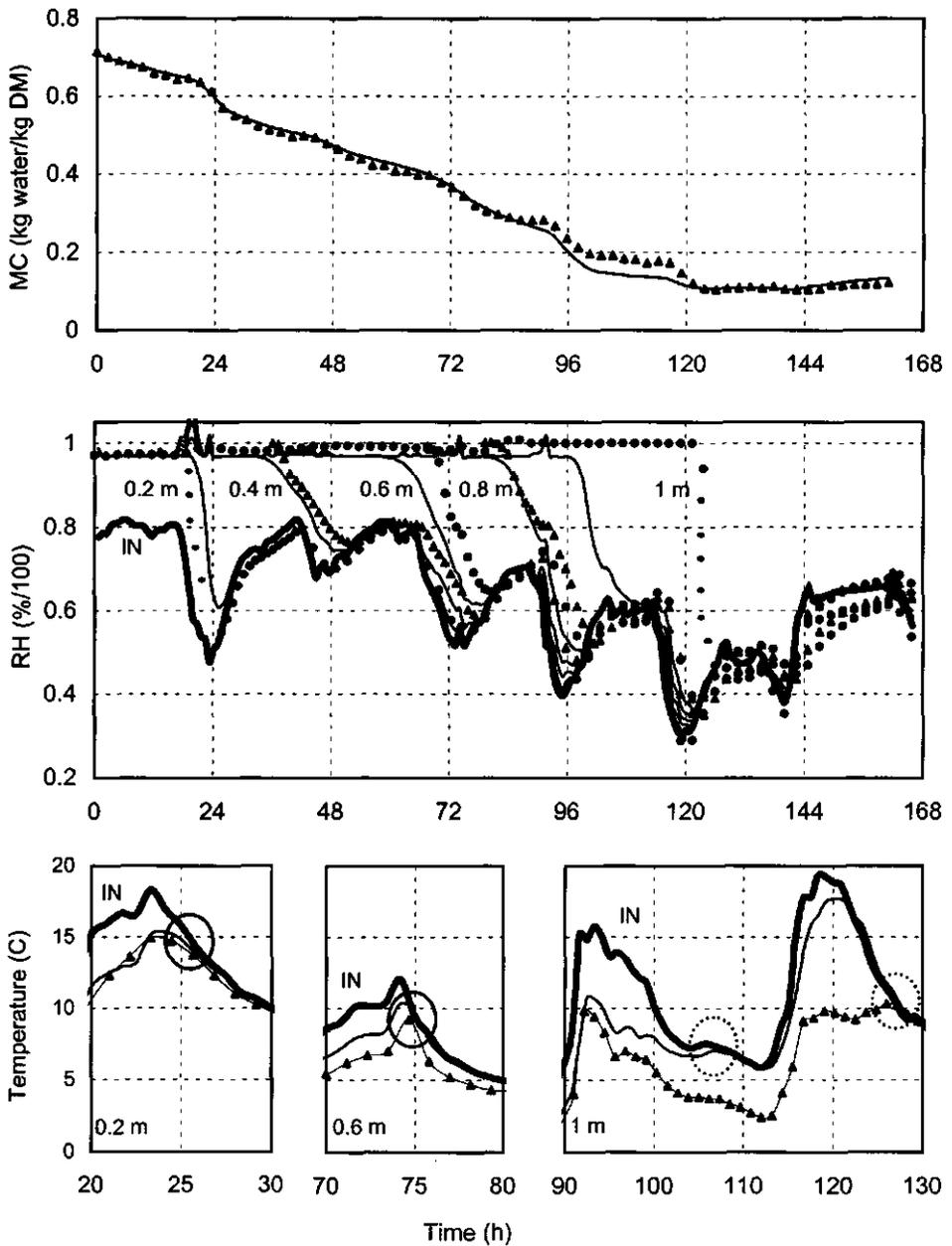


Figure 4: Measured and simulated moisture content of the chip bed (top) and relative humidity (middle) and temperature (bottom) of the ambient air at different heights (0.2, 0.4, 0.6, 0.8 and 1 m) in the chip bed (— = incoming air conditions (IN), ▲, ● = measured data, — = simulations).

In Figure 4 (bottom), the bold line represents the ambient air temperature. At 0.2 and 0.6 m, the simulated air temperature adequately describes the measured temperature. As discussed before, at 1 m, the time delay is due to the fact that condensation was not incorporated into our drying model.

4.2 Possibilities of drying willow chips in a potato store

The costs of drying willow chips in a potato store are time dependent (Figure 5) because in dry months, the amount of air needed to evaporate a certain amount of water is smaller than in wet months. The storage height has little effect on drying costs: the drying time increases with storage height, but the higher drying costs are largely compensated by a higher chip volume. From September until February (in some cases even for a longer period), a potato store is normally used for potatoes and, thus, not available for chip drying. However, this period is economically not interesting due to unfavourable drying air conditions (Figure 5). The evaluation is focussed on the period from March to September. Energy costs for fan electricity vary from 12 to 25 EURO.(t DM)⁻¹. The drying time varies from 21 to 100 days at a storage height of 1.1 m and more than 4 m, respectively.

Costs (EURO/t DM)

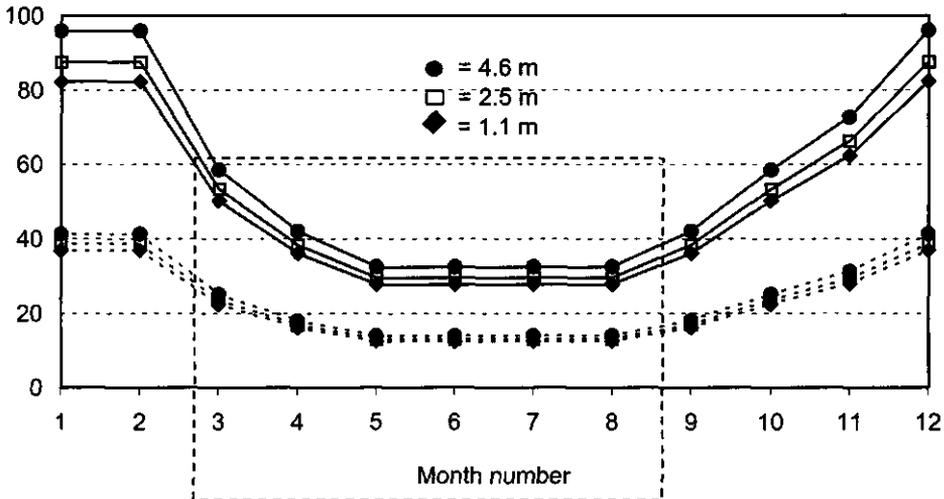


Figure 5: Energy costs (-----) and total costs (—) of forced convective drying of willow chips in a potato store at different storage heights; the dashed window indicates the period which is focused on.

Total costs, which include energy costs and investment costs for the share that facilities are used for chips, range from 28 to 59 EURO.(t DM)⁻¹. Energy costs are on average 44% of the total costs. It seems realistic to assign only energy costs to willow chips, because the overall profit of all activities determines the total farmer's income. Figure 5 also shows that May to August is most profitable for drying but then, the period between harvest (November to March) and drying is at least 1 month, which causes additional handling and intermediate storage problems (such as DM-losses and internal heating). Thus, in reality, drying costs will probably be close to costs in March which is 25 EURO.(t DM)⁻¹.

The cost calculations are based on assumptions with respect to initial and target moisture content, technical possibilities, costs, weather conditions etc. A smaller chip size (<10 mm) increases the pressure drop and, thus, causes higher drying costs. A lower initial or higher target moisture content will decrease the drying costs. From October to March, drying times of up to 300 days were calculated because it was assumed that drying took place with the drying air conditions of one particular month. However, the period October to March was not focussed on. For the other months, the error due to this assumption is small because drying air conditions do not vary as much as from October to March. The calculations attempt to indicate the order of magnitude of the drying costs. Handling costs for filling and emptying the potato store were not incorporated here, but they will increase the total drying costs. The calculations show that drying costs for willow chips at agricultural facilities can be considerable, compared to for example harvest costs [12-14 EURO.(t DM)⁻¹] and, thus, can become a considerable cost factor in the supply chain [Lyons et al., 1989].

5 Conclusions

A PDE deep bed drying model was developed to describe forced convective drying of willow chips. The model, which was validated experimentally for bed moisture content, air temperature and relative humidity, adequately described ambient air drying in a 1 m willow chip bed. Drying air left the bed constantly saturated until the chips were at equilibrium moisture content. A sharp drying front was observed in the chip bed. At the top layers of the chip bed, due to vapour condensation (which was not incorporated into the model), the drying rate was overestimated.

The energy costs of drying willow chips at farm facilities for potato storage and drying were time dependent and ranged from 12 to 25 EURO.(t DM)⁻¹. March to August was the most suitable period for drying, due to favourable ambient weather conditions. Drying costs were hardly influenced by storage height. If investment costs of the facilities were assigned to willow during use for willow, costs ranged from 28 to 59 EURO.(t DM)⁻¹. The costs of continuous forced convective drying of

willow chips using farm facilities can become a considerable factor in the total costs of the supply chain compared to, for example, harvest costs.

The PDE drying model is an appropriate tool to gain insight into the forced convective drying process of willow chips. To estimate the drying time for willow chips, a simple approach, assuming that drying air leaves the chip bed always saturated at wet bulb temperature, is correct and sufficient.

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Notation

a_{int}	power law fit parameter for diffusivity, -
a_{th}	thermal diffusivity, $m^2 \cdot s^{-1}$
a_w	water activity, -
A	area, m^2
c_{pa}	specific heat of air, $J \cdot kg^{-1} K^{-1}$
c_v	specific heat of water vapour, $J \cdot kg^{-1} K^{-1}$
c_w	specific heat of water, $J \cdot kg^{-1} K^{-1}$
c_{wo}	specific heat of wood, $J \cdot kg^{-1} K^{-1}$
C	water concentration, $kg \cdot m^{-3}$
C_{av}	average water concentration of the wood chip, $kg \cdot m^{-3}$
C_e	equilibrium water concentration, $kg \cdot m^{-3}$
$C_{t,L}$	water concentration at the surface of the wood chip, $kg \cdot m^{-3}$
D_e	diffusivity of water in air, $m^2 \cdot s^{-1}$
D_{eff}	effective diffusivity of water in wood, $m^2 \cdot s^{-1}$
D_0	initial diffusivity of water in wood, $m^2 \cdot s^{-1}$
DM	dry matter, kg
h	height of the chip bed, m
h_v	heat of desorption of water, $J \cdot kg^{-1}$
H	water concentration of air, $kg \text{ water} \cdot (kg \text{ dry air})^{-1}$
k	mass transfer coefficient, $m \cdot s^{-1}$
k_1	fit parameter for pressure drop, $Pa \cdot s \cdot m^{-2}$
k_2	fit parameter for pressure drop, -
L	diffusion distance (half the smallest chip dimension), m
M	average moisture content of wood, $kg \text{ water} \cdot (kg \text{ DM})^{-1}$
ΔP	pressure drop, Pa
S^2_{data}	data variance, -
S^2_{mod}	model variance, -

t	time, s
T_a	air temperature, K
T_{wo}	wood temperature, K
v	air velocity, $m.s^{-1}$
V	volume, m^3
x	space coordinate in a single willow chip, m
X	space coordinate in the willow bed, m
α	heat transfer coefficient, $W.m^{-2}K^{-1}$
$\beta_1, \beta_2, \beta_3$	fit parameters of Halsey equation, -
ε	bed porosity, -
λ	thermal conductivity, $W.m^{-1}K^{-1}$
μ	dynamic viscosity, $kg.m^{-1}s^{-1}$
ρ_a	air density, $kg.m^{-3}$
$\rho_{a,i}$	water concentration of air at the wood surface, $kg.m^{-3}$
$\rho_{a,b}$	water concentration of air in the bulk, $kg.m^{-3}$
ρ_{wo}	wood density, $kg DM.m^{-3}$

$$A_{sp} = \frac{1 - \varepsilon}{L} \quad \text{specific surface area, } m^{-1}$$

$$D_p = \frac{6V}{A} \quad \text{equivalent particle diameter, m}$$

$$m = \frac{C - C_e}{C_o - C_e} \quad \text{dimensionless moisture concentration, -}$$

$$U = \alpha A_{sp} \quad \text{bed heat transfer coefficient, } W.m^{-3}K^{-1}$$

$$Nu = \frac{\alpha D_p}{\lambda} \frac{\varepsilon}{1 - \varepsilon} \quad \text{Nusselt number, -}$$

$$Pr = \frac{\mu C_{pa}}{\lambda} \quad \text{Prandtl number, -}$$

$$Re = \frac{v \rho_a D_p}{\mu(1 - \varepsilon)} \quad \text{Reynolds number, -}$$

$$R_{adj}^2 = 1 - \frac{S_{mod}^2}{S_{data}^2} \quad \text{fraction of variance accounted for, -}$$

5

Natural wind drying of willow stems

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Abstract

The natural wind drying process of willow (*Salix viminalis*) stems in large piles was investigated. A simple drying model was provided for stems. Large scale drying experiments were conducted and drying data were statistically analysed. It was investigated whether drying in a pile of willow stems was uniform. After harvest, during storage until August the average pile moisture content was reduced from about 1.0 to between 0.2 and 0.3 kg water.(kg DM)⁻¹, which approximates the equilibrium moisture content. Moisture diffusion within a willow stem is a long term process which is governed by the relative air humidity and ambient temperature. Evaporation of moisture at the outside of a willow stem is a short term process which is governed by rainfall, wind and global radiation. Within a single willow stem, the moisture content was more or less uniform. A pile of willow stems dried uniformly, except for the top of the pile, which forms only a small part of the pile. Covering the pile had no long term effect on the moisture content. The results of natural drying of willow stems indicate that storage of willow stems in large piles is an efficient low cost drying method.

1 Introduction

Willow short rotation coppice (*Salix viminalis*) gains increasing interest as biomass fuel. However, willow is more expensive than other biomass fuels such as forest thinnings and prunings. Measures that decrease the costs of delivered willow fuel per unit of energy are necessary. Cost reduction can be achieved by reducing the production costs of willow coppice, the supply costs to an energy plant (logistics), and the energy conversion costs. The supply costs of willow which amount to 10 to 20% of the total costs [Coelman et al., 1996] depend on the time span between harvest and energy conversion. If the time span is less than half a year, a combination of harvest as chips and forced convective drying at the farm is the cheapest option. If this time span is around half a year or longer, a combination of harvest as stems and natural wind drying is cheaper than harvest as chips and forced drying [Gigler et al., 1999a]. Drying is advantageous with respect to the conversion efficiency and gaseous emissions of the energy plant [Riley and Drechsel, 1983; Lyons et al., 1989; Van den Broek et al., 1995; Liang et al., 1996]. Forced convective drying of chips was described by Gigler et al. [1999c]. This paper deals with natural wind drying of willow stems.

The advantage of stems is their suitability for long term storage with low DM-losses and low microbial activity. The moisture content of stems in a pile can be reduced at very low cost by natural wind drying [Thörnqvist, 1985; Jirjis, 1995a; Mitchell, 1995; Nurmi, 1995; Gigler et al., 1999a]. Several experimental studies have been reported on storage and drying of willow stems [Lyons et al., 1989; Nurmi, 1995; Kofman and Spinelli, 1997; Nellist, 1997a]. These studies describe overall initial, final, and sometimes intermediate moisture contents. However, for stems the

drying process as such has not been described in detail yet. Information concerning the spatial distribution of moisture in willow stems in large piles is lacking. Understanding of the mechanisms that govern the natural wind drying process of willow stems in large piles enables optimization of the process parameters in order to profit from the advantages of stem storage.

The objectives of the current study are, *firstly*, to investigate the mechanism of natural wind drying of willow stems stored in large piles, *secondly*, to provide a simple drying model, and *thirdly*, to investigate the spatial distribution of the moisture content of willow stems stored in large piles. Large scale drying experiments were conducted and the obtained drying data were statistically analysed. A mechanistic drying model was set up to analyse and explain the experimental results.

2 Theory

It is assumed that in a large pile of willow stems uniform drying occurs because in the pile the rate of refreshment of drying air is much larger than the flux of water from the willow stems. A willow stem is surrounded by a bark with a very low diffusivity limiting the drying process which causes a very low water flux [Gigler et al., 1999b]. With respect to the airflow resistance, for stems, no hydraulic data are available. However, for chunks (size: 50-250 mm), a very low airflow resistance was reported compared to chips [Arola et al., 1988; Mivell, 1988; Sturos, 1991; Seres et al., 1999] which indicates that the airflow resistance of stems is also very low. As a consequence, drying air can easily penetrate a pile of willow stems, leading to a high rate of refreshment of the air. Thus, the air conditions in the pile are probably equal to those of the ambient air.

For willow stems, a relatively simple drying model is established in this section. In this model, rainfall and global radiation are not taken into account. It is assumed that they have little effect on the internal drying process of the stems in the pile because the evaporation rate is much larger than the absorption rate of water into the stem. Rain attaches only to the surface of the wood and this water evaporates fast during dry periods. Absorption of water is very slow due to the low bark diffusivity compared to the evaporation rate. Global radiation affects only a small part of the pile, viz the top.

2.1 Statistics

The assumption of uniform pile and stem drying is validated by statistical analyses of the results of large scale drying experiments of piles of willow stems.

Investigation of uniform pile drying: Large piles of willow stems were stored outside during several months. At regular time intervals, stems were sampled for moisture

content at different positions in the piles (see section 3.3). The moisture content data were statistically analysed to investigate whether drying in the pile was uniform. At different sample times, the variation of the moisture content of a stem at a certain position was compared to the variation of the moisture content of a stem at other positions in the pile. A Generalised Linear Mixed Model [GLMM; Engel and Keen, 1994] was applied to investigate whether the moisture content of willow stems differed significantly between different positions in the pile, and whether these differences were time dependent. A GLMM can account for dependency between the observed moisture contents of stems. If the variance (moisture content of the stems) is not constant, a GLMM can also account for this. The so-called Restricted Maximum Likelihood (REML) procedure [Robinson et al., 1982; Robinson, 1987] of the Genstat statistical software package [Genstat 5 Committee, 1993] was used to analyse the GLMM.

Investigation of uniform stem drying: Samples with different diameters were taken of each stem to determine the moisture content (see section 3.3). These data were statistically analysed to investigate whether uniform drying occurred within a single stem. The data were also analysed with a GLMM.

2.2 Drying of a willow stem

A single willow stem can be regarded as a non-shrinking infinite long cylinder (length/diameter \gg 1) of homogeneous wood material, surrounded by a bark. The bark is a thin layer with a high resistance to water transport and prevents the stem from drying out [Gigler et al., 1999b]. Radial water transport in a willow stem can be described as a function of time and place with a diffusion equation for a cylinder according to Crank [1983]:

$$\frac{\partial C}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_{\text{eff}} \frac{\partial C}{\partial r} \right) \quad (1)$$

In the bark ($R_i < r < R$), D_{eff} is equal to the effective water diffusivity of the bark $D_{\text{eff,bark}}$, and at the inner part of the stem ($r \leq R_i$), D_{eff} is equal to the effective water diffusivity of the wood $D_{\text{eff,int}}$. Equation (1) can be solved by one initial and two boundary conditions. The initial condition describes a homogeneous initial moisture concentration:

$$t = 0, \quad 0 < r < R, \quad C_{0,r} = C_0 \quad (2)$$

The first boundary condition describes symmetry around the centre of the cylinder:

$$t > 0, \quad r = 0, \quad \frac{\partial C}{\partial r} = 0 \quad (3)$$

The second boundary condition describes the moisture transfer to the air. The diffusive flux at the edge ($r=R$) is equal to the difference in air moisture concentration at the surface of the wood $\rho_{a,i}$ and in the drying air $\rho_{a,b}$, multiplied by the mass transfer coefficient k .

$$t > 0, \quad r = R, \quad -D_{\text{eff,bark}} \frac{\partial C_{i,R}}{\partial r} = k(\rho_{a,i} - \rho_{a,b}) \quad (4)$$

Basically, equation (4) describes the drying rate of willow stems in connection with the concentration profile in the stem. In the right hand part of equation (4), $\rho_{a,i} - \rho_{a,b}$ represents the driving force for drying. Drying occurs for $\rho_{a,i} > \rho_{a,b}$, rewetting occurs for $\rho_{a,i} < \rho_{a,b}$. All possible factors contributing to internal moisture transfer are lumped into the effective diffusivity of water D_{eff} . The dependency of the diffusivity on moisture content is described with a power law relation of the dimensionless moisture concentration m [Coumans, 1987; Gigler et al., 1999b]:

$$D_{\text{eff}} = D_0 m^a \quad (5)$$

where D_0 and a are fit parameters which can be temperature dependent. In equation (5), a describes the moisture concentration dependence of D_0 . For the bark, $D_0 = D_{0,\text{bark}}$ and $a = a_{\text{bark}}$, for the inner part of the stem $D_0 = D_{0,\text{int}}$ and $a = a_{\text{int}}$ [Gigler et al., 1999b].

The mass transfer coefficient k in equation (4) can be estimated by the empirical relation $Sh=f(Re,Sc)$ for a hollow cylinder [Whitaker, 1972]:

$$Sh = 1.86 Re^{0.33} Sc^{0.33} \left(\frac{L}{2R}\right)^{-0.33} \quad (6)$$

The water sorption isotherm describes the water activity a_w at the surface of the wood which is in equilibrium with the relative humidity of the air. The water sorption isotherm was based on the Modified-Halsey equation for constant temperature [Chen and Vance Morey, 1989]:

$$a_w = \exp(\beta_1 M^{\beta_2}) \quad \text{for } M > 0 \quad (7)$$

At constant air temperature ($T_a=20$ °C), β_1 and β_2 are -0.017 and -1.6794 , respectively. The drying model of a willow stem with bark is represented by equations (1-7).

3 Materials and methods

3.1 Willow stems

The natural wind drying experiments with willow stems (*Salix viminalis* L.) took place in 1997 (March 1 - October 27) and from December 18, 1997 to November 18, 1998. For the former experiments ('1997'), three years old willow stems were harvested in February 1997. For the latter experiments ('1998'), four years old willow stems were harvested in December 1997. Stems were harvested with a whole stem harvester (Segerslåt Empire 2000). Moisture contents were determined by drying at 105 °C during 72 hours [ASAE, 1994]. At the start of the drying experiments, the initial average moisture contents were 0.94 ± 0.04 and 0.95 ± 0.06 kg water.(kg DM)⁻¹, in the '1997' and '1998' experiments, respectively.

3.2 Experimental design

The willow stems were piled up on the headland of the willow fields immediately after harvest. All stems were positioned with the butt side (where the stem was cut from the stools) into the same direction. The side with the butts was defined as the front of the pile. Pile height and stem position were measured at the front. To eliminate edge effects, all piles were either placed against each other, or the left and right side walls were covered with plastic foil. A meteorological station, located a few meters from the willow piles, recorded relative humidity, temperature, wind speed and rainfall.

Experiments '1997': Two piles were erected (see Table 1 for specifications). One pile was erected on a metal frame which was supported by four load sensors (type HBM, 50 kN). Total pile mass was recorded every hour by a data logging unit (Datataker DT500). The other pile was erected on the ground. This pile was denoted as 'uncovered pile' to indicate analogy with the 'uncovered pile' of the '1998' data.

Table 1: Specifications of the willow stem piles.

Year	Lay out	Dimensions l x w x h (m ³)	Initial mass (*10 ³ kg)	Duration (d)	Number of rows	Number of sample stems ^a
1997	sensor	7.9 x 5.8 x 2.6	12	240	4	1-3
1997	uncovered	10 x 6.5 x 3.6	19	240	4	1-3
1998	sensor	7.9 x 7 x 2.3	11	336	4	2-4
1998	uncovered	7 x 7 x 3.6	21	336	3	2-4
1998	covered	7 x 7 x 3.6	21	336	3	2-4

^a Number of stems samples in each row at each sampling time

Experiments '1998': Three piles were erected (Table 1). One pile was erected on a frame with load sensors. Total pile mass was recorded every hour. The other piles were again erected on the ground. One pile was covered on top with a thick cotton sheet to prevent penetration of rain into the pile. The other piles were uncovered.

3.3 Sampling methods

Just before the experiments started, side branches of sample stems were removed to enable stem extraction for moisture determination from the piles during the experiment. All sample stems were marked. During piling, sample stems were placed into the piles in distinguished horizontal rows at several heights (Figure 1, specifications given in Table 1):

- one bottom row, at a height of 0.4 to 0.8 m, defined as row 1;
- one or two middle rows, at a height of 1 m and 2 m, respectively, defined as row 2 and 3;
- one top row, on top of the piles, defined as row 3 (in case of three rows) or 4 (in case of four rows).

Each row contained 25 to 40 sample stems. At regular time intervals, randomly selected stems were removed from each row of the piles for moisture determination. Compared to the total number of stems in each pile, the number of sample stems was small (<0.05%). Consequently, it was assumed that removal of sample stems did not influence the drying process in the pile. Near the centre of each pile, the temperature was monitored by three thermocouples.

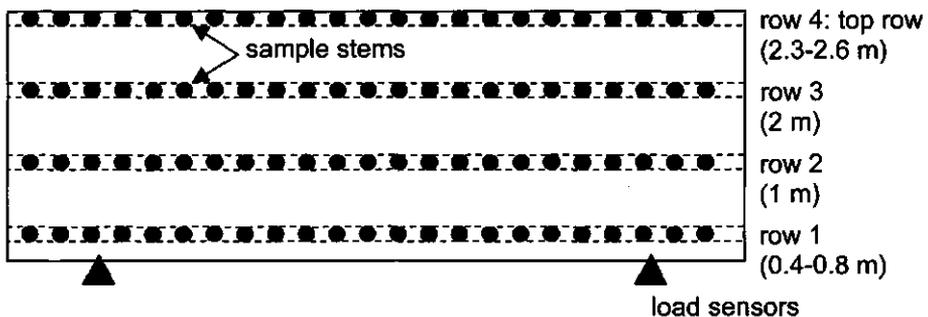


Figure 1: Schematic front view of the sensor pile showing the positions of rows (height) and sample stems.

During the '1997' experiments, sampling took place biweekly. From each sample stem, eight samples were taken. Samples of the stems were taken at equidistant stem positions, but only where the bark was still present. During the '1998'

experiments, the sampling method was changed compared to '1997'. Statistical analyses showed that more sample stems per row at each sample time were desired, and that a lower sampling frequency was appropriate, while the number of samples per stem could be decreased. Sampling in '1998' took place monthly. Four samples were taken from each stem. Diameter and moisture content were determined of all samples. From all samples of one stem, the weighed average stem moisture content was calculated.

3.4 Mathematical solutions of the drying equations

The diffusion equation (1) was solved numerically by discretisation with the finite difference method of Crank-Nicolson. Equation (4) was solved with an Euler forward finite difference method. The equations were programmed in MATLAB [The MathWorks, 1999]. Input parameters were temperature, relative humidity and velocity of the drying air and the material characteristics (diffusivity, stem radius and initial moisture content). Output parameter was the average moisture content as a function of time. The following parameters were used for equation (5): $D_{0,int}=3.0 \cdot 10^{-10}$ m.s⁻², $a_{int}=0.3$, $D_{0,bark}=2.25 \cdot 10^{-12}$ m.s⁻² and $a_{bark}=-0.4$ [Gigler et al., 1999b]. Model simulations were conducted for different sample diameters, which were calculated as the average from all piles and rows of the '1998' data (Table 2).

Table 2: Average sample diameters (10^{-3} m) of the 1998 drying experiments, which were taken at equidistant stem positions (sample a=sample with largest diameter, sample d=sample with smallest diameter).

Pile		a	b	c	d
Sensor	min	20	17	14	9
	average	33	26	21	16
	max	46	36	30	23
Covered	min	20	17	13	10
	average	32	26	21	15
	max	46	36	29	22
Uncovered	min	23	19	14	9
	average	33	26	21	16
	max	43	37	30	23
Total average^a	-	33	26	21	16

^a used for model simulations

The ambient temperature and relative humidity from December 1997 to November 1998 were input parameters. The air velocity was assumed to be 0.1 m.s⁻¹, which is

feasible for air velocities within a pile. Moreover, the influence of (changes in) the air velocity is very small, because the bark largely limits the drying process. The initial moisture content of the simulations was $0.95 \text{ kg water.}(\text{kg DM})^{-1}$ which was equal to the measured value in the '1998' experiment.

4 Results and discussion

4.1 Field drying experiments

During natural wind drying of willow stems in large piles, basically two different drying processes can be distinguished:

1. Diffusion of moisture within the stems, which is a very slow process due to the low bark diffusivity. Relative humidity and ambient temperature are important factors governing this long term process.
2. Evaporation and rewetting at the outside of the stems, which is a relatively fast process. Rainfall, wind and global radiation are important factors governing this short term process.

These two processes are elaborated in this section.

For the 1997 and 1998 experiments, drying curves based on load sensor data are presented in Figure 2 together with rainfall data. It should be noted that sometimes, the amount of rainfall was too small to be recorded or visualised in Figure 2. At the beginning of the drying experiments, during periods with a low relative air humidity (and no rainfall), the moisture content of the piles decreased fast due to the high driving force for drying.

The lowest average moisture content [$0.2\text{-}0.3 \text{ kg water.}(\text{kg DM})^{-1}$] was realised around August in both years, although the 1998 drying experiments started more than two months earlier than the 1997 experiments. The low moisture content was due to favourable drying conditions (low relative humidity, relatively high ambient temperature) on the whole during the summer period. From September onwards, the average moisture content increased somewhat due to a higher ambient relative humidity and lower temperature, which caused a higher equilibrium moisture content in the wood. It can be concluded that, despite differences in rainfall, the moisture content can be reduced from about 1 (at harvest) to $0.2\text{-}0.3 \text{ kg water.}(\text{kg DM})^{-1}$ in August by natural wind drying. These results are in agreement with trends reported by Lyons et al. [1989], Nurmi [1995], Kofman and Spinelli [1997] and Nellist [1997].

The drying curves of Figure 2 show that during rainy periods, the average moisture content usually increased. Rain settled as superficial moisture on the stems which increased pile mass temporarily only, because after rainfall the peaks swiftly disappeared.

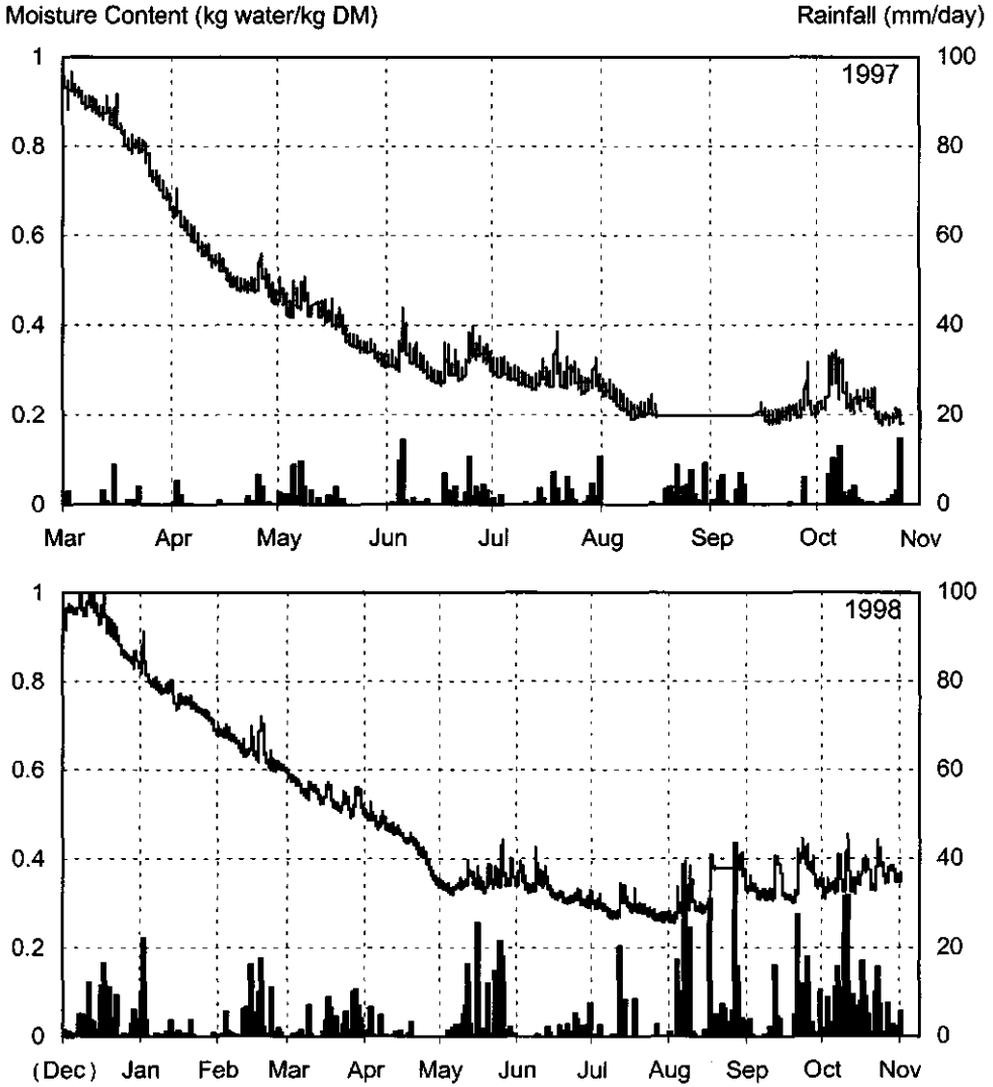


Figure 2: Drying curves of piles of willow stems, based on load sensor data (upper lines), and rainfall data (bottom histograms), for 1997 and 1998 (note: first datapoint in 1997: March 1; first datapoint in 1998: December 18, 1997).

Rainfall mainly interrupted the drying process for a few hours or days, while the internal moisture content was hardly affected. Apparently, the low bark diffusivity limited the rewetting process. During the 1997 experiment, the amount of rainfall was

approximately 400 mm (total 1997: 590 mm), which was less than half the amount of rainfall (ca 990 mm) during the 1998 experiment (total 1998: 1,060 mm). The average rainfall in the Netherlands is ca 800 mm per year. The higher amount of rainfall in 1998 caused a higher average relative humidity, which explains the higher minimum moisture content during 1998, despite the longer storage period. In Figure 2, the small daily fluctuations in the drying curves were probably due to the day-night rhythm of the ambient temperature, which slightly affects the load sensors. Temperature measurements in the piles indicated (data not shown) that the internal pile temperature followed the ambient temperature. No internal heating occurred and microbial activity in the piles was very low. Straight lines in Figure 2 are due to data logging problems (1997: mid August - mid September; 1998: first half of September).

In Figure 3, for each pile the average moisture content of all sample stems together with the average moisture content based on the load sensor data are presented. The drying curves show good similarity. The 1998 load sensor data show a higher average moisture content from July on. The probable reason is that rain attached superficially to the wood, increasing the total mass. The moisture content in the stems hardly increased due to the low bark diffusivity.

Figure 3 shows that the drying curves of 1998 of the covered and uncovered piles are very close to each other. Despite the large amount of rain in 1998, no difference in drying curves was found between the covered and uncovered pile. This observation strongly indicates that rainfall does not directly affect the moisture content of stems in a pile. A statistical analysis of the moisture content, comparing the piles of one experimental year, could not be performed because the number of piles was too small. Calculations will demonstrate that the influence of rain on the stems in the pile is very small. During the experiment, the total amount of rain falling on and into a pile was approximately 990 kg water per m^2 or $990 \text{ mm} \cdot \text{m}^2$. From the experimental data, the total amount of water to be evaporated from the pile was calculated to be about 138 kg per m^2 of pile surface or $138 \text{ mm} \cdot \text{m}^2$. Indicative measurements showed that the amount of stems in the pile approximates 300 per m^3 . Assuming an average radius of $2 \cdot 10^{-2} \text{ m}$, the specific surface is approximately $38 \text{ m}^2 \cdot \text{m}^{-3}$ or $87 \text{ m}^2 \cdot (\text{m ground area})^{-2}$. After a heavy shower of 20 mm, a water film of only about 0.3 mm is left on the stems assuming that rain water is spread evenly over all stems in the pile. This water film will be evaporated quickly as soon as the rain stops. Consequently, covering a pile seems not necessary.

4.2 Statistical analyses

From the data set, several outliers were removed (total number < 1%), because the moisture contents of these outliers were physically not possible (too high moisture contents compared to the average, or negative moisture contents).

Moisture Content (kg water/kg DM)

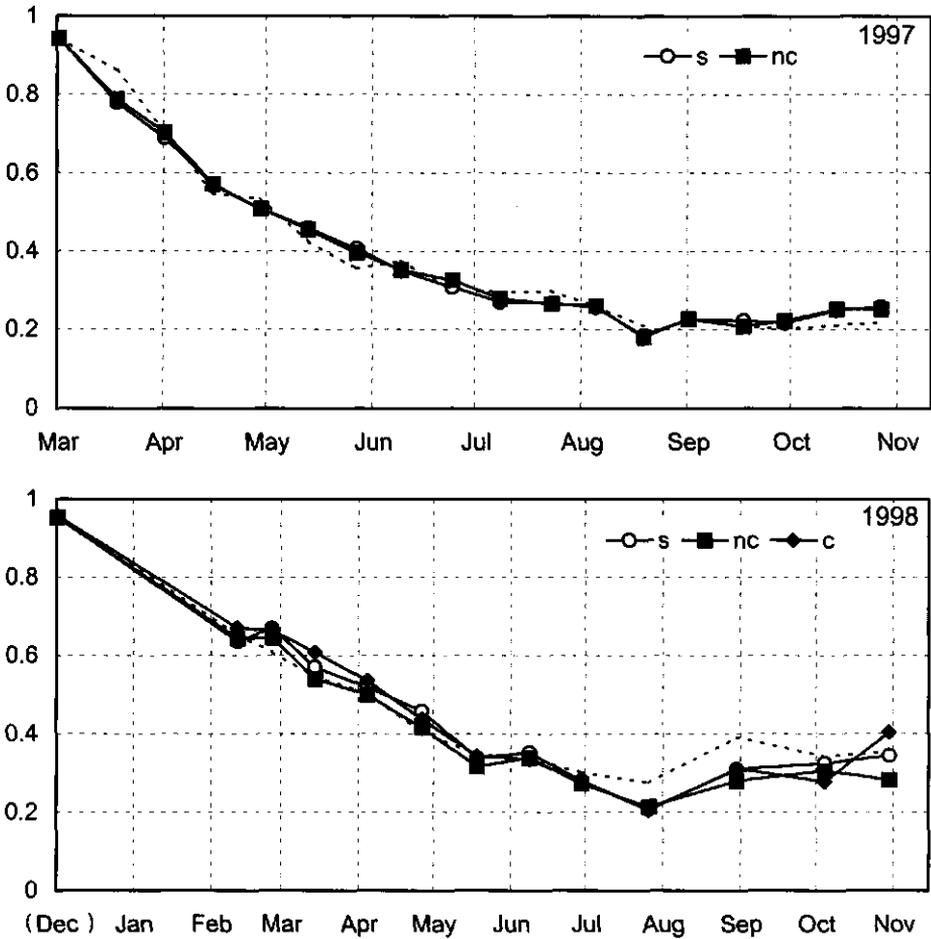


Figure 3: Drying curves of all piles of willow stems, based on sample stems (lines with markers) and load sensor data (dashed lines), for 1997 and 1998 (s=sensor pile, nc=non-covered pile, c=covered pile; note: first datapoint in 1997: March 1; first datapoint in 1998: December 18, 1997).

4.2.1 Investigation of uniform pile drying. Generally, in all piles of 1997 (Table 3) and 1998 (Table 4), natural wind drying was more or less uniform, except for the top row. Drying of the top row (sometimes) differed significantly from drying of the other rows. The difference was probably due to direct exposure of the top of the pile to rain, wind

and radiation. Because the top row forms only a small part of the pile, the effect on the average pile moisture content was very small. The assumption that a pile dried uniformly was thus confirmed.

Table 3: Effect of row on the average moisture content of a stem (1997 experiment).

Rows ^a	4-1	4-2	4-3	3-1	3-2	2-1
Sensor pile	***b,c	***	***	-	-	-
Uncovered pile	*	-	**	-	-	-

^a Rows 4-1 denotes a comparison of row 4 to row 1

^b Significant effects are indicated as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

^c Explanation: in the sensor pile, the moisture content of row 4 (top row) was significantly ($p < 0.001$) different from the moisture content of row 1 (bottom)

Statistical analysis of the 1997 data revealed that differences with respect to stem drying in the piles were not time dependent. Comparing the top row to the other rows in the pile, only between row 4 and row 2 of the uncovered pile no significant difference with respect to stem drying was found (Table 3).

Statistical analysis of the 1998 data (Table 4) showed that differences with respect to stem drying in a pile significantly depended on time. These differences were mainly found between the top row (row 4 of the sensor pile, row 3 of the other piles) and the other rows. Significant differences in absolute terms were in the range of 0.05 to 0.1 kg water.(kg DM)⁻¹. Between the other rows in the piles, drying was uniform.

In Table 4, three drying stages are indicated (drying, equilibrium and rewetting) based on Figure 2. Significant differences mainly occurred in the drying (20% of all measurements) and rewetting (40% of all measurements) stages. The top row rewetted faster in the rewetting stage, probably because rain settled mainly on top of the piles, causing the fastest moisture increase. Differences did not occur during all sampling times within a stage, which was probably due to intermittent periods with and without rain. Only the covered pile showed some significant differences during the equilibrium stage. A good explanation for this can not be given.

4.2.2 *Investigation of uniform stem drying.* Within a single stem, it was expected that the part with a small diameter dries faster than the part with a large diameter. When the stem radius doubles, the circumference also doubles, but the volume increases four times. Consequently, assuming that the resistance of the bark to water transport is identical at all stem diameters, when the willow bark limits the drying process, the drying time doubles.

Table 4: Effect of row and sampling time on the average moisture content of a stem (1998 experiment).

Time	Rows ^b	Sensor pile ^a					Covered pile ^a			Uncovered pile ^a			
		4-1	4-2	4-3	3-1	3-2	2-1	3-1	3-2	2-1	3-1	3-2	2-1
72	drying ^c	-	-	-	-	-	-	**	**	-	**	**	-
86	"	-	-	-	-	-	-	-	**	-	-	*	-
103	"	-	-	-	-	-	-	-	-	-	-	*	-
124	"	***d,e	-	*	-	-	-	-	-	-	-	-	-
146	"	**	-	-	-	-	-	-	*	-	-	-	-
168	"	-	-	-	-	-	-	-	***	***	-	-	-
189	equilibrium	-	-	-	-	-	-	*	-	-	-	-	-
210	"	-	-	-	-	-	-	*	*	-	-	-	-
237	"	-	-	-	-	-	-	-	*	-	-	-	-
272	rewetting	-	-	-	-	-	-	**	**	-	**	***	-
307	"	*	-	-	-	-	-	***	***	-	-	-	-
336	"	***	***	**	-	-	-	-	**	-	***	***	-

^a Sensor pile had four rows; covered and uncovered pile had three rows; 1 is bottom row, 3 or 4 are top rows

^b Rows 4-1 denotes a comparison of row 4 to row 1

^c The drying process is divided into three stages, denoted as drying, equilibrium and rewetting

^d Significant effect are indicated as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

^e Explanation: in the sensor pile, on day 124 the moisture content of row 4 (top) was significantly ($p < 0.01$) different from the moisture content in row 1 (bottom)

The 1998 data were statistically analysed. The sample with the largest diameter was defined as 'a', the sample with the smallest diameter was defined as 'd'. The average diameters of the stems of the 1998 experiment are presented in Table 2. The 1997 data were not analysed due to an insufficient number of repetitions for such an analysis.

The analysis showed that, generally, drying within a stem was more or less uniform. Significant differences between samples of a single stem were time dependent (Table 5). Of all samples, 7% of the sensor pile, 9% of the covered pile and 18% of the uncovered pile dried significantly different from other samples of the same stem. Significant differences were mainly found between the largest (or one to largest) and smallest (or one to smallest) samples (a-d, a-c, b-d), mainly in the bottom (row 1) and top row (row 4 for the sensor pile, row 3 for other piles). In Table 5, the three drying stages described before are indicated (drying, equilibrium and rewetting).

Table 5: Effect of sample diameter (indicated by a to d), sample position (represented by row) in the pile and sample time on the moisture content of a sample (1998 experiments). The number denotes row(s) in which a significant difference was found ($p < 0.05$).

Time	Sensor pile ^a				Covered pile ^a				Uncovered pile ^a									
	a-d	a-c	a-b	b-d	b-c	c-d	a-d	a-c	a-b	b-d	b-c	c-d	a-d	a-c	a-b	b-d	b-c	c-d
72 ^c drying ^d	2,3	-	-	-	-	-	1,2	-	-	-	-	-	1,2,3	1	1	3	-	-
86	-	-	-	-	-	-	1,2	2	-	-	-	-	1	1	-	1	-	-
103	1	-	-	-	-	-	1	1	1	-	-	-	1	1	1	3	-	-
124	1	-	-	-	-	-	1	1	1	-	-	-	1	1	-	-	-	-
146	1	-	-	-	-	-	-	-	1	-	1	-	1	-	-	-	-	-
168	1,4	-	-	1	-	1	-	-	-	-	-	-	1,2	1,2	-	1	-	-
189 equilibrium	-	-	-	1	-	-	-	-	-	-	-	-	-	1,3	-	-	1,2	-
210	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
237	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
272 rewetting	-	-	1,4	1,4	1,4	-	-	-	-	-	-	-	1,3	3	3	1,3	1	1
307	-	-	-	-	-	-	1,3	-	1,3	-	3	-	1	-	-	-	-	-
336	4	-	-	4	-	-	-	-	-	-	-	-	1,3	3	-	1,3	2	3

^a Sensor pile had four rows; covered and uncovered pile had three rows; 1 is bottom row, 3 or 4 are top rows

^b Samples 'a'- 'd' denotes a comparison of sample 'a' (largest diameter) to 'd' (smallest diameter)

^c Explanation: in the sensor pile, on day 72, in row 2 and 3, the moisture content of sample 'a' was significantly different from the moisture content in sample 'd'

^d The drying process is divided into three stages, denoted as drying, equilibrium and rewetting

Significant differences predominantly occurred in the drying and rewetting stages, because then the effect of the stem diameter on the drying rate is most profound. However, only few differences were found with respect to drying. This strongly indicates that, within the stem, water is probably redistributed by capillary flow of water from the large to the small part of the stem.

4.3 Drying model simulations

For the average sample radii of the 1998 experiment (see Table 2), model simulations [equations (1-7)] were conducted and compared to the experimental drying curve of 1998 (Figure 4).

Moisture Content (kg water/kg DM)

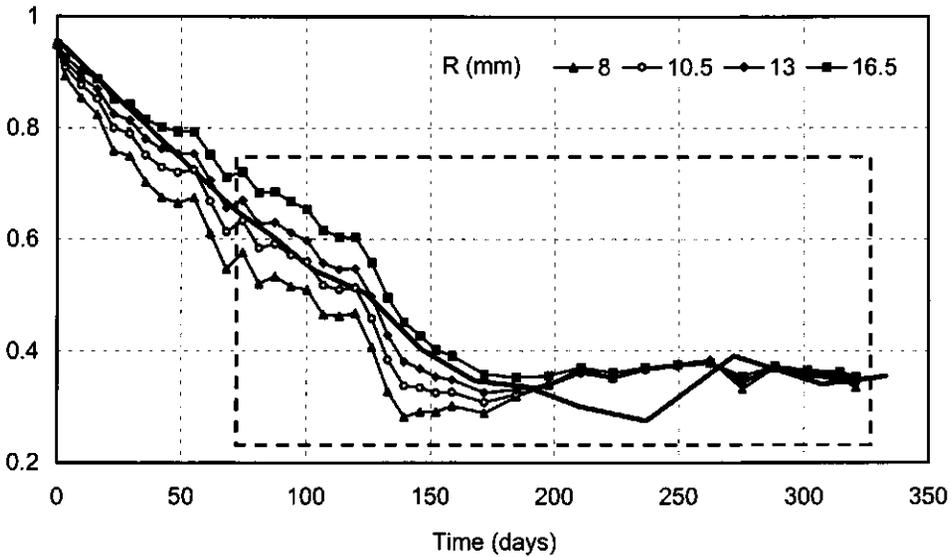


Figure 4: Drying curves (lines with markers) of the average stem radii of the stems in the 1998 experiment, based on model simulations with the actual ambient temperature and relative humidity of that year. The bold line represents the experimental drying curve of the whole pile based on load sensor data (Figure 2). The dashed window indicates the sampling period.

Drying was simulated with the actual ambient temperature and relative humidity data of the 1998 experiment. Due to the difference in air temperature during the drying experiment (-5 to 30 °C), the effective diffusivity (using an Arrhenius type equation) of the bark and the wood was corrected for the ambient temperature, because initially, the diffusivity was determined at 20 °C.

Figure 4 shows that, at the beginning of the drying process, at high moisture contents [range 0.4 to 1 kg water.(kg DM)⁻¹] and favourable ambient conditions, a sample with a small radius (R=8 mm) dried faster than a sample with a large radius (R=16.5 mm). Between a moisture content of 1 to 0.6 kg water.(kg DM)⁻¹, when the diameter doubled (R=8 mm versus R=16.5 mm), the time to reach the same moisture content approximately doubled. Based on this observation, between samples, more differences would be expected during the drying stage (Table 5). However, the small number of differences indicates that water is redistributed within the stem. When the equilibrium stage is reached (around 190 days), all drying curves merge which confirms that in this stage hardly any differences were found between the samples.

5 Conclusions

The following conclusions are drawn with respect to natural wind drying of willow stems in large piles:

- After harvest, during storage until August, the average pile moisture content can be reduced from about 1 to between 0.2 and 0.3 kg water.(kg DM)⁻¹, which is close or equal to the equilibrium moisture content, even during a wet year.
- Moisture diffusion within a willow stem is a long term process which is governed by the relative air humidity and ambient temperature. Evaporation of moisture at the outside of a willow stem is a short term process which is governed by rainfall, wind and global radiation.
- A pile of willow stems dries more or less uniformly, except for the top of the pile which is more prone to ambient weather conditions than the rest of the pile. However, the top forms only a small part of the pile, and thus, has little influence on the average pile moisture content.
- Covering a pile had no long term effect on the moisture content.
- Within a single willow stem, the moisture content is more or less uniform which indicates that water is internally redistributed.

The good results of natural drying of willow stems indicate that storage of willow stems in large piles is an efficient low cost drying method.

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Notation

a	power law fit parameter for diffusivity, -
a_{bark}	power law fit parameter for diffusivity, -
a_{int}	power law fit parameter for diffusivity, -
a_w	water activity, -
C	water concentration, kg.m^{-3}
C_0	initial water concentration, kg.m^{-3}
$C_{0,r}$	initial water concentration at a radial coordinate, kg.m^{-3}
C_e	equilibrium water concentration, kg.m^{-3}
$C_{t,R}$	water concentration at the surface of the willow stem, kg.m^{-3}
D_a	diffusivity of water in air, $\text{m}^2.\text{s}^{-1}$
D_{eff}	effective diffusivity of water in a medium, $\text{m}^2.\text{s}^{-1}$
$D_{eff,bark}$	effective diffusivity of water in the bark, $\text{m}^2.\text{s}^{-1}$
$D_{eff,int}$	effective diffusivity of water in the wood, $\text{m}^2.\text{s}^{-1}$
D_0	initial diffusivity of water in a medium, $\text{m}^2.\text{s}^{-1}$
$D_{0,bark}$	initial diffusivity of water in the bark, $\text{m}^2.\text{s}^{-1}$
$D_{0,int}$	initial diffusivity of water in the wood, $\text{m}^2.\text{s}^{-1}$
DM	dry matter, kg
k	mass transfer coefficient, m.s^{-1}
L	length, m
M	water content of wood, $\text{kg water}.\text{(kg DM)}^{-1}$
t	time, s
T_a	air temperature, $^{\circ}\text{C}$
r	radial coordinate in a willow stem, m
R	stem radius, m
R_i	radius at the transition between bark and wood, m
v	air velocity, m.s^{-1}
β_1, β_2	fit parameters of Halsey equation, -
μ_a	air dynamic viscosity, $\text{kg.m}^{-1}\text{s}^{-1}$
ρ_a	air density, kg.m^{-3}
$\rho_{a,l}$	air water concentration at the wood surface, kg.m^{-3}
$\rho_{a,b}$	air water concentration in the bulk, kg.m^{-3}

$$m = \frac{C - C_e}{C_0 - C_e} \quad \text{dimensionless moisture concentration, -}$$

$$Re = \frac{v\rho_a(2R)}{\mu_a} \quad \text{Reynolds number, -}$$

$$Sc = \frac{\mu_a}{\rho_a D_a} \quad \text{Schmidt number, -}$$

$$Sh = \frac{k(2R)}{D_a} \quad \text{Sherwood number, -}$$

6

On optimization of agri chains by dynamic programming

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Abstract

A methodology for optimization of agri chains by Dynamic Programming (DP) is presented which explicitly deals with the appearance and quality of products. In agri chains, a product can be characterised by two types of states, namely appearance and quality states. Appearance states are influenced by handling actions. Quality states are influenced by processing, transportation and storage actions. The concept of chain optimization by Dynamic Programming (DP) is elaborated. Chain optimization refers to the construction of optimal routes defining which actors in the chain should perform which actions at which process conditions at minimum integral costs. Models describing quality development of a product as a function of the process conditions can be included into the DP methodology. The DP methodology has been implemented into a software tool and is illustrated with a case for an agri chain of willow biomass fuel to an energy plant.

1 Introduction

The design of supply chains of agricultural commodities like dairy products, fruits and flowers can be complicated because in each link of the supply chain, the quality of a product is influenced intentionally and unintentionally. This quality development, which can be regarded as an undesired (deterioration) as well as a desired (ripening) process, should be taken into account when designing supply chains. For sake of distinction, in this paper we define two types of supply chains: 'agri chains' and 'non-agri chains'. Agri chains are defined as supply chains of products of agricultural origin, although products which originate from other than agricultural sources (such as chemical products) could also fit into the methodology we will present for agri chains. Non-agri chains are defined as supply chains of other than agricultural commodities. In non-agri chains, product quantities are moved from one place to another while undergoing different changes intentionally (handling). Generally, during transportation and storage of non-agri products, the product characteristics remain unchanged. For agricultural commodities, however, transportation and storage can considerably affect product quality. For instance, a high ambient temperature during transportation of milk accelerates the development of micro-organisms and, thus, influences milk quality.

To preserve the quality of a product in the agri chain, expensive measures are taken such as cooling, controlling air conditions or prevention of incidence of light. If the effect of these measures on product quality is known, and the associated costs are given, they can be included into a model of the agri chain and used for chain optimization. The objective of our study is to present a methodology for optimization of agri chains by Dynamic Programming (DP) which explicitly deals with both product quality development and product appearance. Our aim is not to present a new DP technique, but to elaborate the application of DP to optimize agri chains. Chain

optimization is defined as the design of agri chains which should reach target product specifications at minimum costs. All activities in the agri chain are tuned integrally, in contrast to optimizing each actor individually. DP [e.g. Winston, 1997] is an appropriate tool for optimizing supply chains. DP offers the possibility to include parameters describing the state of a product and it can cope with non-linearities regarding the factors which influence the states of a product.

Various studies exist on optimization and simulation of agri chains. In a model of Saedt et al. [1999], quality development for vegetables and fruit is taken into account. Their approach considers flows through a network, in which the optimal solution of an MILP (Mixed Integer Linear Programming) model defines the order of the links; the actors in the network are determined simultaneously with the order of handling by the optimal chain design. Jenkins and Arthur [1983] present a method for assessing biomass utilisation options using network analysis and DP focussing on handling operations only. Murata [1987] used DP to determine optimum routes of raw biomass material to a processing factory taking transport distances and biomass enthalpy into account. Zwietering and Van 't Riet [1994] describe the optimization of a cooling chain focussing on the kinetics of food spoilage reactions. De Mol et al. [1997] developed an MILP model to optimize both the network structure and the product types of biomass fuel to an energy plant, in order to gain insight into the logistics of biomass fuel collection. However, time dependent effects like storage of biomass appeared to be difficult to include into their model. Maia et al. [1997] propose an MILP model to optimize capital investment in food preservation facilities for fruits and vegetables. Poot and Hendrix [1996] present a full integer programming model in which appearance states at the end of the link are included, and the chosen chain design originates from allocation of handling to actors in the supply chain. Despite the agricultural character of the product (potted plants), no quality development was taken into account. For wood as an energy source, Sells and Audsley [1991] developed a whole farm linear programming model, but their focus was on calculating the profit of the farm as a whole, instead of the supply chain.

In this paper, the theory section (2) presents a way of considering agri and non-agri chains including quality parameters. In the methodology section (3), the translation of the design of agri chains into DP terminology is explained, based on a one dimensional example. The concept of implementing the DP approach into the software programme MATLAB [The Mathworks, 1999] is given in section 4. Next (section 5), the concept of the DP methodology is illustrated with an example of the supply of willow biomass fuel to an energy plant. Section 6 shows how the influence of time on quality development can be included into our methodology. In section (7), conclusions are drawn.

2 Theory on supply chains

The supply chain of a product consists of several links. We define these links as actors. Examples of actors are a factory, farmer, auction, transporter, wholesaler and retailer (Figure 1).

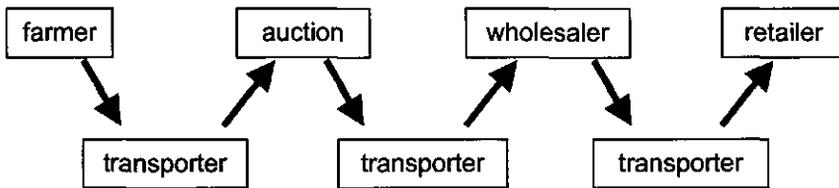


Figure 1: Example of actors in an agri chain.

In non-agri chains, each actor performs actions which intentionally alter or modify product characteristics in such a way that the product reaches the end user according to target specifications. The product characteristics can be represented by one or more product states. During transportation and storage, basically nothing happens to the product states. For a computer, for instance, necessary actions in a supply chain can include computer assembly, software installation, packing in a box, adding cables to the box, labelling, and transportation to and storage at the wholesaler. In our view, the actions which take place in non-agri chains can be grouped into two types:

1. 'handling': actions which alter or modify the state of a product. Examples are packing, wrapping and labelling [e.g. Bowersox et al., 1986; Poot and Hendrix, 1996];
 2. 'transportation' and 'storage': actions which do not alter the state of a product.
- Basically, all handling actions alter the appearance of a product. Consequently, the state of a product can be characterized by so-called 'appearance' states, which describe if a product is (un)packed, (un)labelled, (un)wrapped. Transportation (including (un)loading) and storage do not aim at changing these appearance states.

For agricultural commodities, however, an important feature is product quality, which is continuously liable to changes. Examples of quality parameters are the number of micro-organisms per unit volume of milk, or the ripeness of a banana. In agri chains, this continuous process is referred to as quality development which can be slowed down or accelerated. Changes are, in general, irreversible. Quality development of agricultural commodities is largely based on biological, physical and

chemical processes [Zwietering, 1993]. The following factors influence quality development [Zwietering and Van 't Riet, 1994]:

- process conditions, which are ambient conditions influencing product characteristics, such as temperature, relative humidity, light intensity, concentration of gasses and physical force on the product;
- throughput time in a link during which the product is exposed to the process conditions;
- appearance state of the product, such as packing and particle size.

For example, a high ambient temperature (process condition) stimulates the growth of micro-organisms in milk (quality development), and the duration of exposure (throughput time) determines the final micro-organism concentration. However, for milk stored in an insulated container (appearance), the effect on quality is less compared to bottled milk (appearance) [Zwietering and Van 't Riet, 1994]. Consequently, in agri chains, in contrast to non-agri chains, we propose to characterize agricultural commodities with the following two types of states:

- 'appearance' states, describing if a product is (un)packed, (un)wrapped, (un)labelled or cut into pieces;
- 'quality' states, describing the quality which can be expressed as micro-organism infestation, ripeness, moisture content, colour, taste.

As a result, we distinguish the following three types of actions in agri chains:

1. 'handling': actions which intentionally alter or modify the appearance states of a product. Examples are wrapping, cutting and labelling [Poot and Hendrix, 1996];
2. 'processing': actions which intentionally alter or modify the quality states of a product. Examples are cooling and drying [Zwietering and Van 't Riet, 1994];
3. 'transportation' and 'storage': actions which intentionally and unintentionally alter the quality states of a product.

In some cases, it is not obvious whether an action should be defined as handling or processing, for example extrusion of food. If an action changes the quality of a product, we suppose this action should be defined as processing. Moreover, the definition of an action, whether it is handling or processing, does not influence our approach of chain optimization.

The control of process conditions during handling, processing, transportation and storage can be costly. For instance, a low temperature during transportation requires expensive conditioned transportation. The effects of handling on the appearance states of agricultural products are described as a change from one discrete appearance state into another. The effect of processing on the quality of agricultural products requires the description of a continuous process. Quality states can be described as measurable parameters which can take any value within a certain range. Given models which describe the physical, chemical and biological changes,

due to specific process conditions and the associated costs, it is possible to optimize step wise decision problems of agri chains. Thus, we define the objective of designing agri chains as the alteration or modification of the initial appearance and quality states of agricultural commodities, in such a way and at such process conditions, that the target states are reached at minimum total chain costs. The definition of the target states is product dependent. For some products, a penalty cost function can be used if the target states are not reached (for example: ripeness) while for other products, this could mean that the product becomes worthless (for example, micro-organism infestation of milk). In our approach, the agri chain consists of several pre-defined actors (Figure 1), whose positions in the chain are fixed. All actors may perform certain actions on the product. Chain optimization refers to the construction of routes defining which actors should perform which actions (handling, processing, transportation and storage) at which process conditions, in order to achieve minimum total chain costs.

3 Methodology in DP terminology

In this section, the DP terminology for agri chains is explained. An agri chain consists of a series of actors (Figure 1). Each actor can perform one or more of the actions handling, processing, transportation and storage, in order to alter the appearance and quality states of a product. Chain design is the allocation of actions to actors. We introduce the following DP definitions [Winston, 1993]:

- qs:** quality state of a product, 'qs' is determined by process conditions, appearance state and throughput time in a link;
- as:** appearance state of a product, 'as' is determined by handling;
- qx:** decision with respect to processing, transportation and storage which affects quality state 'qs';
- ax:** decision with respect to handling which affects appearance state 'as';
- $s_k=(qs,as)$:** state of the product at each stage k ($k=0\dots n$), s_0 is the initial state and s_n is the final or target state;
 → in the agri chain, s_k is the product state at the end of link k ;
- $x_k=(qx,ax)$:** possible decisions with respect to processing, transportation and storage and handling in stage k ;
 → in the agri chain, x_k is a group of possible actions in link k ;
- $c_k(s_{k-1},x_k)$:** costs of decision x_k at stage k for state s_{k-1} ;
 → in the agri chain, c_k are the costs of action x_k based on state s_{k-1} ;
- $s_k=T_k(s_{k-1},x_k)$:** for decision x_k , transformation function T_k describes the change of state s_{k-1} into s_k ;

→ in the agri chain, T_k describes the effect of action x_k on the product state s_{k-1} , leading to a new product state s_k . This process of a decision leading to a new state is repeated until the target state is reached.

The schematic overview in Figure 2 illustrates the development of appearance and quality states in agri chains. It also demonstrates the difference between agri and non-agri chains in our view.

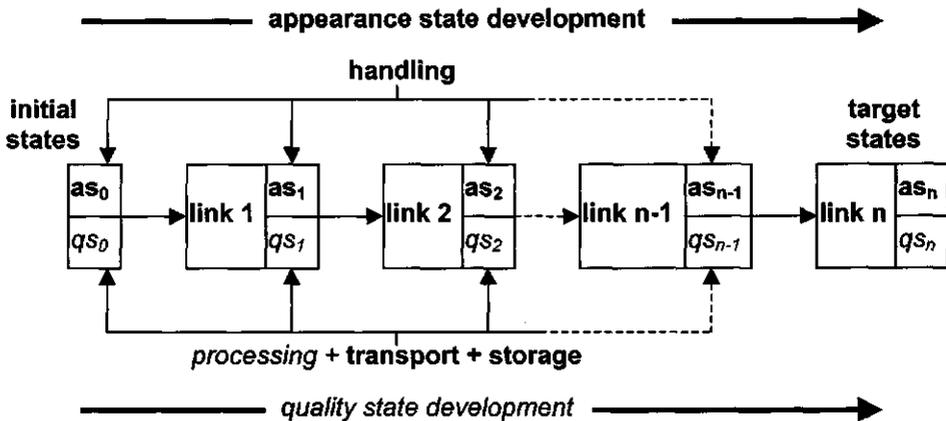


Figure 2: Schematic view of non-agri chains (**bold**) and agri chains (*italic*). For non-agri chains, transportation and storage do not influence the appearance states.

In the conceptual idea of the DP approach, stages coincide with links (which are actors). Practically, the DP approach can be implemented by enumerating the possible actions (and order of the actions) for each actor first, and then, to define the stages as possible actions. In the DP approach, possible chain designs or routes are defined by possible trajectories the product can follow from the initial state $s_0=(as_0,qs_0)$ to the target state $s_n=(as_n,qs_n)$. The chain is calculated backwards (so-called backward recursion), starting at the target state. The 'Bellman equation' calculates the optimal order of handling, processing, transportation and storage and the optimum process conditions at all links for the whole agri chain [Winston, 1993]:

$$V_{k-1}(s_{k-1}) = \min\{C_k(s_{k-1}, x_k) + V_k(T_k(s_{k-1}, x_k))\} \tag{1}$$

Function $V_k(s_k)$ gives, as usual in DP, the costs of the optimal route from state s_k at stage k to the end of the chain. In equation (1), for all possible decisions, the resulting state s_k and corresponding value $V_k(s_k)$ is determined and added to the costs $c_k(s_{k-1}, x_k)$ of decision x_k ; finally, the minimum costs are calculated for all

possible decisions. Recursively, the function V_k ($k=n, n-1, \dots, 0$) is calculated until the initial state s_0 is reached. The underlying costs for the transfer from one state to another are summed. States which are not possible are assigned infinite costs and, consequently, they are never selected in the optimum route. When the initial state is reached, the minimum costs of the supply chain are known, and the consecutive route or chain design. The transformation function T_k consists of, for example, one or more differential equation(s) describing the change of the quality state of a product, using the process conditions as input parameters. The new state can be exactly calculated, but in some cases, it can be more convenient to approximate the quality change with a simple function, in order to reduce the total computation time.

The DP methodology is illustrated with the following one dimensional example, which focuses on the quality state development of a banana. The example does not illustrate the advantage of DP over the full enumeration of all possible routes. The appearance state development (describing whether the banana's are clustered or loose, labelled, packed) will not be discussed in detail in this section, but it is included in a case study for another product in section 5. For a banana, the quality state is represented by its ripeness, for which colour is a good indicator. For reasons of simplicity, we assume that the quality state of a banana is determined by the process conditions light intensity and temperature. If the temperature and/or light intensity is too high, the banana will change quickly from its initial green colour (not ripe) to yellow (ripe) and finally to black (too ripe). A higher temperature and/or light intensity will accelerate quality development. Reducing light intensity is usually not a problem, but reducing temperature (cooling) in agri chains can be expensive.

A simplified supply chain of a banana (Figure 3) consists of the following actors (accompanying actions between brackets): farmer (harvest), ship (transportation), wholesaler (storage), truck (transportation) and retailer (storage). Given models which describe how light intensity and temperature affect banana ripeness, the supply chain can be optimized in such a way that the banana reaches the retailer with its target ripeness at minimum costs. We assume that the quality state s_k of the banana is represented with an indicator with values within the range $[0,40]$. The initial state which is a green banana on a tree is $s_0=0$, the target state is a ripe banana at the retailer according to the customers' wish, which is assumed to be $s_n=35$. The final state should not be too much below $s_n=35$ because then, it will take too long before customers will purchase the banana which causes additional storage costs for the retailer. In that case, it would have been cheaper to transport the banana at a higher temperature and/or light intensity.

The banana supply chain has an infinite number of possible chain designs or routes. Figure 3 shows only three possible routes (A, B and C) for the banana, to illustrate how the quality state of the banana changes from farmer to retailer, and the

associated costs. At stage 0, the effect of harvest on the quality state $s_0=0$ is identical for all routes. In the next stage (transportation by ship), we show three different options. Transportation costs increase from route A to C due to decreasing transportation temperatures from A to C. Consequently, route C has the slowest quality development because a lower temperature slows down the ripening process. Compared to route A and B, at stage 2 (the wholesaler), route C is the cheapest because the quality state allows storage at a higher temperature. At stage 3, during transportation by truck, different process conditions are required at each route in order not to exceed the target quality state requested by the retailer.

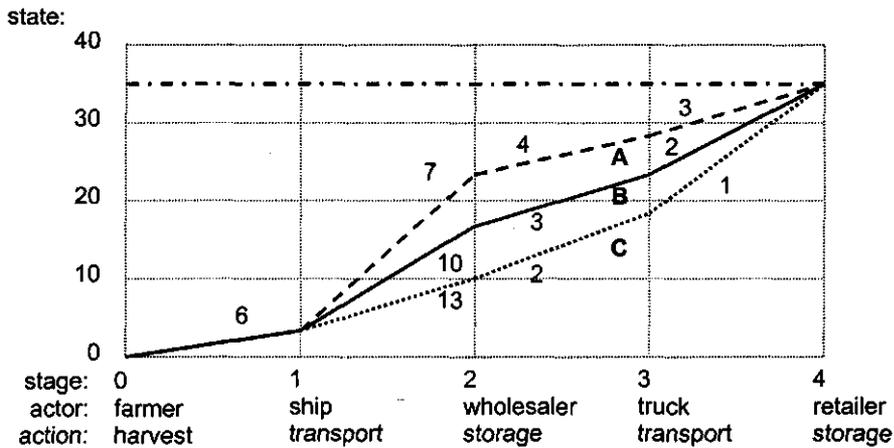


Figure 3: Graphical example of three possible routes (A, B, C) of a banana agri chain. The figures represent the costs at each stage. The horizontal line is the target state which should not be exceeded.

The backward recursion calculating the optimum route of the actions in the supply chain is illustrated for the banana example in Figure 4. Routes and costs are given in Figure 3. Figure 4 shows that, in this example, route A has minimum supply costs.

1. costs from the final stage 4 to stage 3 (transportation by truck):
 route A: $V_3(33)=3$;
 route B: $V_3(28)=2$;
 route C: $V_3(19)=1$;
 2. costs from stage 3 to stage 2 (storage at wholesaler):
 route A: $V_2(29)=4+V_3(33)=7$;
 route B: $V_2(20)=3+V_3(28)=5$;
 route C: $V_2(9)=2+V_3(19)=3$;
 3. costs from stage 2 to stage 1 (transportation by ship):
 route A: $V_1(3)=7+V_2(29)=14$;
 route B: $V_1(3)=10+V_2(20)=15$;
 route C: $V_1(3)=13+V_2(9)=16$;
 $V_1(3)=\min\{14; 15; 16\}=14$.
 4. costs from stage 1 to stage 0 (harvest):
 $V_0(0)=6+V_1(3)=20$.
- Route A is the cheapest with total costs of 20

Figure 4: Cost calculation method for the banana example.

4 Implementation of the DP methodology

In the previous section, the selection of optimum routes, taking quality parameters into account, was presented for a very simple example, which can easily be solved by hand. More complicated problems require the use of computers to find a solution in an efficient way. However, for DP no standard software is available. Some DP problems can be solved with spread-sheet programmes, but incorporation of differential equations into these programmes can be difficult. Therefore, a computational method was developed to solve agri chain optimization problems by DP. This method was implemented in MATLAB, which is a software tool suitable for vector and matrix manipulation [The MathWorks, 1999]. Programming with MATLAB does not require extended programming skills, knowledge of programming basics is sufficient to understand the MATLAB implementation presented here. An important advantage of MATLAB is that external functions can be included into the programme. This is useful for including, for example, non-linear physical models which describe quality development of agricultural commodities at different process conditions. In Figure 5, a general presentation of the DP definitions of the previous section, and the translation into MATLAB terminology is given. Figure 6 presents the generic MATLAB code for calculating the optimum route.

DYNAMIC PROGRAMMING: s_k = possible state values x_k = possible decisions c_k = cost function T_k = transformation function V_k = function containing intermediate optimal valuesBellman equation: $V_{k-1}(s_{k-1}) = \min\{c_k(s_{k-1}, x_k) + V_k(T_k(s_{k-1}, x_k))\}$ **MATLAB:** i = counter for possible state values X = vector of possible decisions x = counter for possible decisions k = counter for stages C = cost vector corresponding to possible decisions W = local vector containing intermediate function values V = function containing intermediate optimal valuesBellman equation: $V = \min\{C+W\}$

Figure 5: Translation of DP definitions into MATLAB.

In Figure 6, line 1 is a 'for-loop' with the length equal to the number of stages. Here, stages are taken equal to possible actions in the agri chain. The 'for-loop' starts at the last stage (stage f) and ends at the first stage (stage 1).

MATLAB:

```

1. for k = f:-1:1;           for all possible stages k
2.   for i = 1:n;           for all possible state values i
3.     for x = 1:m;         for all possible decisions x
4.       C(x) = cost(i,x);  cost vector C for each state i and decision x
5.       snew = trans(i,x); new state snew for each state i and decision x (local)
6.       W(x) = V(snew);   value W for each new state snew (local)
7.       V(i,p) = min(C+W); new function V and its state i
8.     end;
9.   end;
10. end;
```

Figure 6: Generic MATLAB code for calculating the optimum chain design.

The backward recursion is indicated by the negative increment. For the banana example, the number of stages is 5. The counter value of the initial stage (i) is 1 because 0 does not exist as a counter. Line 2 is a 'for-loop' for all possible state

values. For the banana example, the possible values of the quality state ripeness are assumed to run from 0 to 35 with a discretization step of 1 (36 possible values). For ease of use, we take integer values for s . In line 3, a 'for-loop' is given for all four possible actors: ship, wholesaler, truck and retailer. In this case, harvest at the farmer is not incorporated, because the new appearance state after harvest is identical for all routes. Line 4 calculates the costs for each decision x for counter i of all possible state values. Line 5 represents the transformation function, which gives the new (local) value of the state as a result of decision x . The new (local) value W for all possible decisions is calculated in line 6. In line 7, the value for V is determined by selecting the optimum decision (in this case, minimum costs). Variable p is a local counter which is appointed to the optimum decision, p is used by the programme to select the associated state. The procedure is repeated for all values $i=1,\dots,n$ of the quality state and for each stage $k=1,\dots,f$ downwards. Lines 8 to 10 are 'end'-statements for the 'for-loop' of line 1 to 3.

To complete the methodology in MATLAB, the following vectors, matrices and functions are defined:

- cost matrix V :

V represents the optimal costs of the states at each stage. During the optimization procedure V is filled gradually. For the banana example, V is a 5 (number of stages) by 35 (number of possible state values) matrix. The final state value $V(5,35)$ is equal to 0 to indicate that the target state is reached at this point;

- decision vector X :

X consists of m elements each representing a decision (an action);

- cost function C :

C is a function which calculates the costs of a specific transformation. Depending on the decision, costs are simply looked up in a table (for handling actions) or are calculated with an external function (for processing, transportation and storage actions);

- transformation function 'trans':

'trans' calculates the state change as a result of a decision. In MATLAB, 'trans' can be any function containing, for example, a (set of) differential equation(s).

In some cases, transformation function 'trans' and cost function C can be combined into one function with the process conditions and the current state as input parameters, and the new state and the associated costs as output parameters. All restrictions with respect to the decisions in the agri chain can also be put into the transformation function. If a decision can not be taken, 'trans' returns infinite costs, which means that this decision is never selected in the optimum. It should be kept in mind that the total computing time increases with the complexity of the transformation function.

5 Case: supply chain of willow biomass fuel to an energy plant

In this section, a case is presented which discusses the supply of biomass fuel from energy crops to electricity plants [Gigler et al, 1999a]. Several studies were published on biomass supply chain optimization. Huisman and Gigler [1997] argued that interactions in the biomass fuel supply chain require an integral approach of the chain, in order to optimize total costs and energy consumption. Jenkins et al. [1984] made a technical and economic comparison of systems for collecting, processing, storing, and transporting biomass for use in energy systems. De Mol et al. [1997] developed simulation and optimization models for the logistics of biomass fuel collection. Nilsson [1999a,b] described a dynamic simulation model for analysis of various delivery alternatives, in order to improve and optimize performance, and to reduce the costs and energy needed for straw handling. These models focussed mainly on handling operations. De Mol et al. [1997] also incorporated simple relations for fuel quality (DM-losses, moisture content), but in their model, it was not possible to incorporate differential equations describing quality development.

The case presented here briefly discusses handling as well as processing actions in the supply chain of willow biomass fuel. The case is an illustration of the methodology and terminology for biomass fuel supply chains introduced in Gigler et al. [1997]. It does not show the efficiency of DP as such, because only a limited number of actors and possible actions in the chain are chosen. Its intention is to give the reader an overview of the total case and the ability to understand the optimal trajectory at one glance. The case study considers two states, resulting in a two dimensional DP approach. One dimension describes the appearance state development (particle size), the second dimension describes the quality state development (moisture content).

Willow coppice is a biomass fuel which can be grown by farmers. In winter, willow is harvested and after going through a supply chain, the fuel is finally delivered at an energy plant, where the fuel specifications (=target states) should be met. The agri chain of willow starts at harvest and ends at the energy plant. We assume that the agri chain consists of three actors which positions in the chain are fixed: 'farmer', 'transporter' and 'energy plant'. The following actions can be performed at each actor (type of action between brackets):

- farmer:
 - *harvest* (handling), for which three different techniques exist, leading to three different particle sizes: chips (0-50 mm), chunks (50-250 mm) or stems (uncomminuted material);
 - *natural wind drying* (processing) of chunks or stems, which takes place during outdoor storage;

- *forced convective drying* (processing) of chips or chunks with ambient air, which is forced through the material with a fan;
- *size reduction* (handling) of stems and chunks to chips with a small scale chipper;
- transporter: *transportation* from the farm to the energy plant;
- energy plant:
 - *size reduction* (handling) of stems and chunks to chips with a large scale chipper;
 - *thermal drying* (processing) of chips at high temperatures in large scale installations.

In this section, we refer to natural wind drying as natural drying, and forced convective drying as forced drying.

Before harvest takes place, willow coppice has the appearance of a tree at the field with a moisture content (abbreviated as MC) of approximately 50% (wet base, kg water/kg total). At the energy plant, a particle size (abbreviated as PS) of chips is required with $MC \leq 20\%$. The willow agri chain should be optimized in such a way that, before energy conversion at the energy plant takes place, the willow fuel meets the fuel specifications at minimum costs. In other words, MC and PS of the willow should be altered in the agri chain from its initial value (MC=50%, PS=tree) at the farm to its required final value (MC=20%, PS=chips) at the energy plant at minimum costs. MC is the quality state, which is affected by 'processing' and 'storage' actions, PS is the appearance state, which is affected by 'handling' actions. In this case, for willow, the transport distance is not relevant to quality development because the time needed for transportation (order of hours) is very short compared to the time scale of quality development (order of weeks). However, for flowers and milk for example, transportation does play a crucial role in quality development. The state of willow can be described as $s_k=(MC,PS)$. MC is divided into 31 discrete values ranging from 20% to 50%, PS is defined as tree, stem, chunk or chip. Consequently, the initial state is $s_0=(50\%,tree)$, the final state is $s_n=(20\%,chips)$. All possible actions which can take place in the chain are defined as decision $X=[harvest; storage; forced drying; thermal drying; size reduction; transportation]$. Note that natural drying of stems and chunks is not incorporated as a separate decision because it takes place during open storage.

In the example, the following assumptions were made. The natural drying rate for stems and chunks is 4% and 5% absolute/month, respectively. Forced drying takes 1 month, thermal drying takes a few hours only. The total chain duration is fixed at 3 months. Transportation distance is assumed to be 30 km.

In Figure 7, a graphical example of a willow agri chain is presented showing various actions which (at the links) form the stages of the practical implementation of

the DP approach. In the links, the actors can perform one or more of the actions defined by decision X. As an example, six possible routes for particle size chunks (A to F) are shown which are described in Table 1.

Table 1: Possible routes for the calculation example for harvest as chunks.

Route	Actions
A	harvest-transportation-size reduction-thermal drying
B	harvest-storage (natural drying)-transportation-size reduction-thermal drying
C	harvest-size reduction-forced drying-transportation
D	harvest-size reduction-transportation-thermal drying
E	harvest-storage (natural drying)-size reduction-transportation-thermal drying
F	harvest-storage (natural drying)-size reduction-forced drying-transportation

Table 2 presents the costs of all actions. Figure 8 shows the calculation method. Basically, a choice has to be made which of the actions drying (natural, forced and/or thermal) and size reduction should take place and where (at the farm or at the energy plant). Harvest and transportation have to take place in all routes. Figure 8 shows that route F has minimum supply costs of 27.5 EURO/t DM.

Table 2: Cost figures (EURO/t DM) of possible actions of the willow agri chain.

Link		Chips	Chunks	Stems
Harvest		12.3	14.8	13.9
Storage	gravel ^a	0.6	0.7	0.8
Drying	natural ^b	-	0.7	0.8
	forced ^c	0.2* Δ MC	0.3* Δ MC	-
	thermal ^c	0.8* Δ MC	-	-
Chipping	decentral	-	6.4	12.9
	central	-	1.4	2.8
Transportation ^d		0.04	0.04	0.04

^a costs in EURO/month.t DM

^b natural drying costs are equal to storage costs

^c drying costs depend on the difference between initial and final moisture content (20%); Δ MC is in (%absolute) moisture difference; for example, if MC changes from 50% to 20%, Δ MC = 30

^d costs in EURO/km.t DM

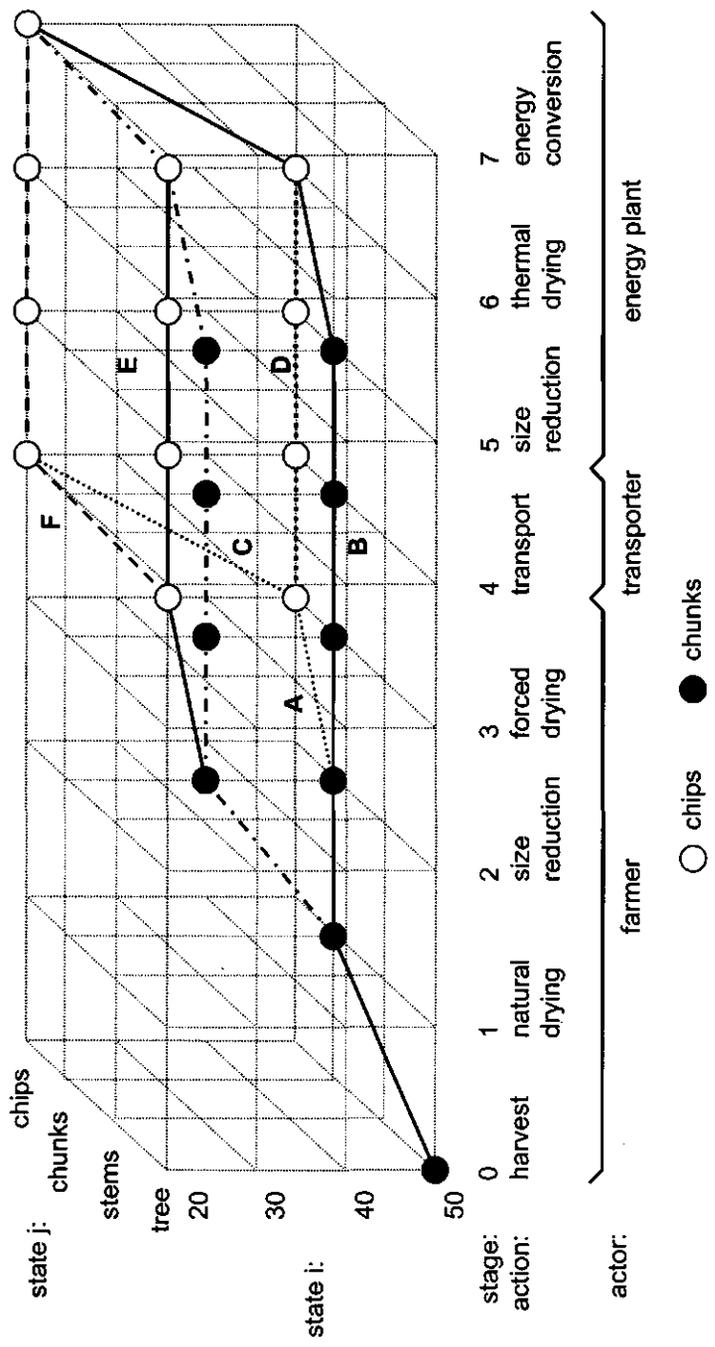


Figure 7: Graphical example of several routes (A to F) of the willow agri chain for chunks.

1. costs from final stage 7 to stage 6 (thermal drying):

$$V_6(50\%, \text{chips})=24$$

$$V_6(35\%, \text{chips})=12$$

$$V_6(20\%, \text{chips})=0$$

2. costs from stage 6 to stage 5 (size reduction):

$$V_5(50\%, \text{chunks})=1.4+V_6(50\%, \text{chips})=25.4$$

$$V_5(35\%, \text{chunks})=1.4+V_6(35\%, \text{chips})=13.4$$

$$V_5(20\%, \text{chips})=0+V_6(20\%, \text{chips})=0$$

$$V_5(50\%, \text{chips})=0+V_6(50\%, \text{chips})=24$$

$$V_5(35\%, \text{chips})=0+V_6(35\%, \text{chips})=12$$

3. costs from stage 5 to stage 4 (transportation, 30 km):

$$V_4(50\%, \text{chunks})=1.2+V_5(50\%, \text{chunks})=26.6$$

$$V_4(35\%, \text{chunks})=1.2+V_5(35\%, \text{chunks})=14.6$$

$$V_4(20\%, \text{chips})=1.2+V_5(20\%, \text{chips})=1.2$$

$$V_4(50\%, \text{chips})=1.2+V_5(50\%, \text{chips})=25.2$$

$$V_4(35\%, \text{chips})=1.2+V_5(35\%, \text{chips})=13.2$$

4. costs from stage 4 to stage 3 (forced drying):

$$V_3(50\%, \text{chunks})=0+V_4(50\%, \text{chunks})=26.6$$

$$V_3(35\%, \text{chunks})=0+V_4(35\%, \text{chunks})=14.6$$

$$V_3(50\%, \text{chips})=\min\{6+V_4(20\%, \text{chips}), 0+V_4(50\%, \text{chips})\}=7.2$$

$$V_3(35\%, \text{chips})=\min\{3+V_4(20\%, \text{chips}), 0+V_4(35\%, \text{chips})\}=4.2$$

5. costs from stage 3 to stage 2 (size reduction):

$$V_2(50\%, \text{chunks})=\min\{6.4+V_3(50\%, \text{chips}), 0+V_3(50\%, \text{chunks})\}=13.6$$

$$V_2(35\%, \text{chunks})=\min\{6.4+V_3(35\%, \text{chips}), 0+V_3(35\%, \text{chunks})\}=10.6$$

6. costs from stage 2 to stage 1 (natural drying):

$$V_1(50\%, \text{chunks})=\min\{2.1+V_2(35\%, \text{chunks}), 0+V_2(50\%, \text{chunks})\}=12.7$$

7. costs from stage 1 to stage 0 (harvest):

$$V_0(50\%, \text{tree})=14.8+12.7=27.5.$$

Route F is the optimum route with total costs of 27.5 EURO/t DM

Figure 8: Calculation of minimum chain costs of chunks for the willow case.

The example in this section demonstrates the selection of the order of actions which have minimum costs over six possible routes through the agri chain only for a limited number of actors and actions. The process conditions are not incorporated correctly yet, because fixed drying rates are used. However, ambient process conditions can affect the natural drying rate, which can lead to smaller or higher moisture contents. In our methodology, the moisture content after forced or natural drying can also be calculated with a (set of) differential equation(s) describing the physical process. DP selects the optimum route from all possible routes through the agri chain. For willow coppice, this is described in detail by Van den Hazelkamp [1998].

6 Optimization of agri chains with time dependent quality parameters

In the previous case, the throughput time of the total agri chain and the throughput time of all actions in the chain were fixed. However, the optimum route through the chain can be time dependent due to time dependency of certain actions. For example, the reduction of the moisture content due to natural drying at the farmer depends on time; generally, the reduction varies between 4 to 5 %absolute per month [Gigler et al., 1999a]. Since natural drying has low costs compared to other actions, it will become more feasible as the total throughput time and, consequently, the throughput time for natural drying increases. This is a general aspect in agri chains: quality development depends on the duration of processes and, therefore, the throughput time of the chain can determine the optimum chain design. In our optimization methodology, time dependency can be included as a separate state variable, which is defined as the total time still available before the target state(s) must be reached. All decisions on actions which take a certain amount of time influence the time still available. A decision can only be taken if the time necessary for the corresponding time dependent action is within the time still available. This restriction applies to decisions on actions which take a significant amount of time. For example, size reduction of willow stems takes a few hours while natural drying takes several months; consequently, the time necessary for size reduction is negligible.

In the MATLAB methodology presented in Figure 6, time dependency is included by introducing an additional state variable which represents the time still available to run through the chain. In MATLAB, we introduce an additional 'for loop' which is defined as the time still available. Each time a decision is taken, the time necessary for the corresponding action is subtracted from the total amount of time still available. Consequently, the time necessary for a decision is included as output parameter in the transformation function. This increases the dimension of matrix V by one. If an action needs more time than the total time still available, this action can not be selected as optimum decision. The inclusion of time as an optimization parameter offers the possibility to optimize agri chains as a function of the total time available, as well as for each time step separately.

In the case of section 5, the throughput time was fixed at three months. Inclusion of time, which is not illustrated here, means that optimization of the willow agri chain is repeatedly executed, for example for month 1 to 12. Thus, for each month, the optimum chain design is calculated, and supply strategies can be derived.

7 Conclusions

In this paper, we proposed a methodology for optimizing agri chains, taking product appearance and product quality explicitly into account. Clear definitions of links, actors, actions and states are given. In our view, non-agri chains deal with the development of appearance states of a product, which are influenced by handling actions. Transportation and storage do not alter the states of a product in non-agri chains. In agri chains, the product is characterised by two types of states, namely appearance states and quality states. Appearance states are influenced by handling actions. Quality states are influenced by processing, transportation and storage actions.

Chain optimization by DP refers to the construction of routes, defining which actors should perform which actions at which process conditions to achieve minimum supply costs. Conceptually, in our DP approach stages are equal to links which are actors. Practically, stages can be defined as actions. Models which describe quality development of a product as a function of process conditions can be included into the DP approach. The DP methodology was implemented into a software tool (MATLAB) and optimum solutions could be determined, which was demonstrated by a case of the willow agri chain.

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7

Discussion and conclusions

The first objective of this thesis was to develop an optimization tool to determine minimum cost supply chains of willow biomass to energy plants. An appropriate tool to optimize supply chains by Dynamic Programming was presented in Chapter 6. The second objective was to develop models to investigate the drying process of willow biomass and the parameters which govern this process. Drying characteristics of willow chips and stems on particle level were described in Chapter 3. Drying models for forced convective drying of willow chips and natural drying of willow stems were described in Chapters 4 and 5, respectively. The third objective was to assess general supply strategies of willow biomass to energy plants. For the situation in the Netherlands, supply strategies were described in Chapter 2. The combination of harvest techniques and appropriate drying methods turned out to be a crucial factor in the selection of minimum cost supply chains.

Analysis of supply strategies revealed that if the time span between harvest and energy conversion was greater than two to three months, harvest as chunks (size 50-250 mm) together with forced convective drying, natural wind drying, or a combination of both drying techniques, yielded a minimum cost chain. Information on chunk drying in Chapter 2 was based on literature. Forced convective drying and natural wind drying of chunks was not detailed in this thesis so far. Therefore, in this chapter drying of chunks is discussed. Next, the supply strategies of Chapter 2 are evaluated by the optimization model of Chapter 6 incorporating the information from Chapters 3-5 on willow drying. To investigate to which degree supply strategies are sensitive to changes of input data, a sensitivity analysis is conducted. Results obtained for willow biomass are generalised for other biomass fuels. Finally, general conclusions are drawn.

Drying of willow chunks

Regarding drying, chunks combine the advantages of both chips and stems. Chunks can be dried relatively quickly by forced convective drying and very cheaply by natural wind drying [Gislerud, 1990; Kofman and Spinelli, 1997; Gigler et al., 1999a]. For forced convective drying, the high pressure drop over a chip bed is a major disadvantage because it causes high energy costs [Mivell, 1988; Westerberg, 1993]. The pressure drop decreases considerably when the particle size increases, and consequently, forced convective drying of chunks requires much less energy than chips [Smith and Riley, 1984; Arola et al., 1988; Gustafsson, 1988; Gislerud, 1990; Sturos, 1991; Kofman and Spinelli, 1997; Seres et al., 1999].

Generally, natural wind drying experiments with different wood species show that chunks in large piles dry well [Frederikson and Rytgard, 1985; Nilsson, 1987; Arola et al., 1988; Baadsgaard-Jensen, 1988; Gjölsjö, 1988; Mitchell et al., 1988; Mivell,

1988; Nurmi, 1988; Gislerud, 1990; Kofman, 1994; Jirjis, 1995a; Kofman and Spinelli, 1997; Nellist, 1997b). These studies report that compared to chips, heat generation within the chunk pile is lower or even absent, microbial activity is negligible in chunk piles, and consequently DM losses are reduced. The drying rate of a pile largely depends on the chunk dimensions. Within limits, natural wind drying improves when the particle size increases because the airflow resistance over a pile decreases. However, quantitative data on the drying process of chunks are often missing.

To investigate chunk drying, together with the natural wind drying experiments on willow stems (Chapter 5), two piles of chunks were erected in 1997. One pile was placed on load sensors that recorded the total pile mass as a function of time (analogous to the stem drying experiments in Chapter 5). The other (control) pile was placed on the ground. Results and experimental information are given in Figure 1. The size of the chunks was determined by sieving [Gigler et al., 1996]: the main fraction (78%) was in the range of 10 to 40 mm, 35% was in the range of 20 to 30 mm. The mean size is smaller than that of the range indicated by the chunk size definition (50 to 250 mm). The experimental drying curve (Figure 1) shows that these particles dried well. Continuous temperature measurements in the pile indicated that the internal temperature followed the ambient air temperature (not shown here). Visual inspection after termination of the experiments showed that microbial degradation in the pile was negligible.

On June 24, samples were taken from the control pile. The moisture content was 0.31 ± 0.04 kg water.(kg DM)⁻¹ which is close to the moisture content in the load sensor pile. At the end of the experiments, in both piles, samples were taken for moisture determination at different positions. The average final moisture content in the control pile (on September 18), 0.24 ± 0.07 kg water.(kg DM)⁻¹, was in agreement with the moisture content in the sensor pile on that date. The final moisture content in the sensor pile (on October 5) was 0.24 ± 0.02 kg water.(kg DM)⁻¹.

To analyse the drying process of chunks in a pile, a forced convective drying model of willow chips (Chapter 4) was used. Model simulations were conducted with the 1997 daily average of ambient temperature and relative humidity. In the model, it was assumed that drying air moves from the front to the back of the pile (the distance front-back is defined as the depth). In the vertical plane, perpendicular to the air flow, homogeneous drying was assumed. Figure 1 shows that this model is an appropriate tool to describe the natural wind drying process of willow chunks. However, optimization of the input parameters of the drying model (such as chunk size, magnitude and direction of the air velocity) is necessary to improve the agreement between simulated and experimental drying curves.

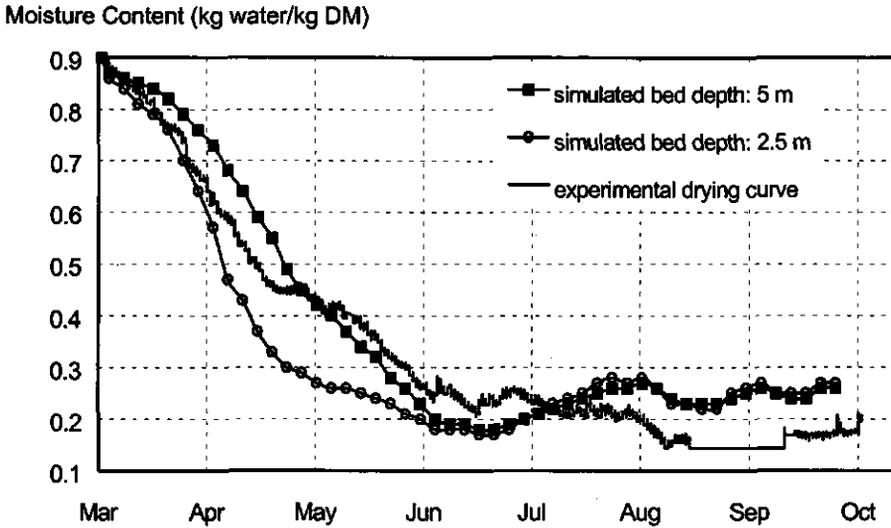


Figure 1: Moisture content of willow chunks as a function of time during natural wind drying. Model simulations were done with 1997 ambient air conditions. The average diffusion distance of the chunks was 1.5×10^{-2} m. Simulated air velocity was 0.2 m.s^{-1} , simulated bed depths were 2.5 and 5 m. Experimental specifications: In 1997, chunks were produced from three years old willow stems (*Salix viminalis*) with a Sasmo HP25 chunker. Two chunk piles were constructed, referred to as the load sensor pile and the control pile. The load sensor pile was covered on top to prevent rain penetrating the pile. Left and right side walls were covered with plastic foil to eliminate side effects. Only front and back sides were open. Of the control pile, only side walls were covered to eliminate edge effects. Dimensions (depth x width x height) of the load sensor pile were $5 \times 1 \times 2.7 \text{ m}^3$ (total mass 2,850 kg) and of the control pile $4.8 \times 3 \times 3.2 \text{ m}^3$ (mass 7,775 kg). Initial moisture content was about $0.9 \text{ kg water} \cdot (\text{kg DM})^{-1}$. The drying experiment took place from March 4 until October 5. The straight line (August-September) is due to data logging problems. Data of the control pile are not shown.

To demonstrate the influence of the pile depth on the drying process, a simulated drying curve for chunks with a bed depth of 2.5 m is included in Figure 1. The depth of the chunk bed influenced the drying time. The smaller pile dried faster. In the constant drying rate period, drying air leaves a wet chunk bed fully saturated which was indicated by model simulations (data not shown). When the bed depth

increases, more drying air is necessary to reach the same moisture content. Thus, the bed depth can be used to control the natural wind drying time of chunks.

Based on information from literature and this thesis, a brief assessment of willow biomass drying techniques is given in Table 1. Although thermal drying is not discussed in detail in this thesis, it is included for completeness.

Table 1: Assessment of drying techniques for different particle sizes of willow.

Particle size	Natural wind drying	Forced convective drying	Thermal drying
Chips	-- ^a microbial degradation, high DM-losses, no drying	+	+
		fast drying process, high energy costs due to high airflow resistance	small particle size causes fast release of water
Chunks	++ low airflow resistance, low DM-losses, fast drying process	++ low airflow resistance, fast drying process	-- particle size too large for fast release of water
Stems	++ low airflow resistance, low DM-losses slow drying process	-- slow drying process due to bark	-- particle size too large for drying installation, slow drying due to bark

^a categories: -- (very unfavourable) to ++ (very favourable)

Generally, to accommodate drying, the chunk size should be small in order to limit the diffusion distance, and thus the drying time. However, the particle size should be large enough to maintain a low airflow resistance in the chunk bed to enable air to reach all positions in the bed easily.

Forced convective drying is not always possible because ambient air conditions depend on the local weather. Generally, drying air conditions are less favourable during the night than during the day because of higher relative humidity and lower temperatures. Therefore, instead of continuous forced convective drying, an intermittent forced convective drying regime, controlled by the relative humidity, the temperature of the drying air and the actual moisture content of the willow fuel would be more efficient. This regime reduces the costs because the ventilation equipment only operates when air conditions are such that drying occurs [Gustafsson, 1988; Kofman and Spinelli, 1997; Nellist, 1997b].

Evaluation of supply strategies of willow biomass to energy plants

In Chapter 2, supply strategies of willow biomass to energy plants were derived for the situation in the Netherlands. Data were largely based on literature information. For missing data, 'guestimations' were made. Information on natural wind drying and forced convective drying was especially lacking. The data from Chapters 3 through 5 and the information on chunk drying in this chapter filled the gap.

The information on drying can be used to optimize supply chains of willow biomass to energy plants. The supply strategies and costs reported in Chapter 2 were recalculated. Instead of the simulation model, the optimization model described in Chapter 6 was used. Basically, all data were identical to those of Chapter 2, except for the following:

- *Forced convective drying costs of willow chips and chunks.* Chapter 4 showed that the period March-August was most suitable for forced convective drying of chips. Energy costs ranged from 12-25 EURO.(t DM)⁻¹. Costs of drying to reach the final moisture content at the energy plant were determined as a function of the initial moisture content [from 0.33 to 1 kg water.(kg DM)⁻¹]. Handling costs were also included. The drying costs of chunks were calculated using the same methodology. Drying costs of chunks were close to those of chips: the bed height of chunks is higher than of chips, but the bulk density is lower.
- *Thermal drying costs of willow chips.* In Chapter 2, the size of the drying installation was based on the total amount of water to be dried in each supply chain. Here, the approach was simplified. A rotary dryer was selected with a capacity of 30,000 t DM.y⁻¹, assuming that a quarter to a fifth of the total fuel needed (around 130,000 t DM) should be dried thermally. Costs of drying to reach the final moisture content were calculated as a function of the initial moisture content [from 0.33 to 1 kg water.(kg DM)⁻¹], using the method described by Van 't Land [1991]. The use of waste heat was not incorporated.

Initially, the willow trees have a moisture content of 1 kg water.(kg DM)⁻¹. The final specifications at the energy plant are a moisture content of 0.25 kg water.(kg DM)⁻¹, and a particle size of chips or chunks for combustion, and chips only for gasification.

The following four optimal supply strategies are distinguished, based on the chain calculations for different energy conversion options:

1. Immediate supply strategy

Energy conversion takes place immediately after harvest, without storage. The supply chain consists of: harvest as chips – transportation – thermal drying at the energy plant.

2. Short term supply strategy

Energy conversion takes place within two months after harvest. The supply chain consists of: harvest as chips – forced convective drying at the farm – (transportation) – (storage).

3. Medium term supply strategy

Energy conversion takes place within five months after harvest. The supply chain consists of: harvest as chunks – natural wind drying on the headland – forced convective drying at the farm – (transportation) – (size reduction to chips).

4. Long term supply strategy

Energy conversion takes place at least six months after harvest or later. The chain consists of: harvest as chunks – natural wind drying on the headland – (transportation) – (size reduction to chips).

Certain actions are between brackets to indicate that these actions are not always necessary to deliver the fuel to the plant, or to comply with the plant's fuel specifications. For example, for small scale energy conversion, it was assumed (Chapter 2) that handling comprises transportation because the plant is located near the willow fields.

Table 2: Optimal supply strategies of willow to energy plants, as a function of the time span (months) between harvest and energy conversion, for different conversion technologies and scales, together with the range of supply costs.

Supply Strategy ^a	Large scale		Small scale		Costs ECU.(t DM) ⁻¹
	Gasification	Combustion	Gasification	Combustion	
<i>Immediate</i>	0	0	NA ^b	NA ^b	54
<i>Short term</i>	1-2 ^c	1	1-3	1	28-33
<i>Medium term</i>	3-5	2-5	4-5	2-5	20-32
<i>Long term</i>	6-12	6-12	6-12	6-12	15-21

^a Immediate: harvest as chips-transportation-thermal drying

Short term: harvest as chips-forced drying-(transportation)-(storage)

Medium term: harvest as chunks-natural drying-forced drying-(transportation)-(size reduction)

Long term: harvest as chunks-natural drying-(transportation)-(size reduction)

^b Not applicable, thermal drying is too expensive at small scale energy plants

^c Explanation: for large scale gasification, for a time span of 1 or 2 months between harvest and energy conversion, the optimal supply strategy is *Short term*

For the medium term supply strategy, under favourable weather conditions, natural wind drying of chunks in small piles (instead of forced convective drying) may be sufficient to meet the specifications set by the energy plant, because the drying time

can be controlled by the pile dimensions (bed depth). For the long term supply strategy, harvest as stems and natural wind drying is a good alternative to chunks because the costs of both supply chains are similar.

The selection of a specific supply strategy depends on the time span between harvest and energy conversion and the type and scale of energy conversion technology (Table 2). The partition of the costs over the different actions in the supply chains (Appendix I and II) shows that, in case thermal drying is necessary, this action represents the largest cost factor (70%). Therefore, thermal drying is only selected when energy conversion takes place immediately after harvest. If this is not the case, harvest (20-80%) or, if necessary, forced drying (20-50%) are the most expensive actions in the supply chain. The share of size reduction and transportation is equal (15-20%). The share of natural wind drying and storage is less than 3%.

The recalculated supply strategies and those of Chapter 2 are largely identical. The supply costs show some differences. Due to a better understanding of the drying processes and the factors governing drying, better estimations and cost calculations may be made. Basically, the design of the supply chain depends on the possibilities of natural wind drying and forced convective drying because these drying techniques are alternatives, respectively, to forced convective and thermal drying which are more expensive. The time span between harvest and energy conversion determines if natural wind and forced convective drying are possible. Supply of willow to gasification plants is generally more expensive than supply to combustion plants, because the particle size requirements of gasification are stricter (chips only). In case of chunks, additional size reduction is required for gasification. However, the energy conversion efficiency of gasification is higher which means that less fuel is needed to produce the same amount of energy. Consequently, when costs are expressed per unit of energy produced, gasification is cheaper [Gigler et al., 1999a].

Sensitivity analysis on optimal supply chains

A sensitivity analysis was conducted to investigate the robustness of supply strategies to changes in cost figures and other assumptions, such as drying rates. The sensitivity analysis was only done for large and small scale gasification. For combustion, the resulting trends were identical. Only one factor was changed at a time. Where possible, changes were based on realistic assumptions (thermal drying, natural drying rate). In other cases, changes were large enough to ensure that differences occurred (e.g. harvest costs) or to demonstrate that even big changes did not affect the optimal chains (e.g. transport distance).

Table 3: Effect of single alterations on the selection of supply strategies for large and small scale gasification and the resulting optimal chains (strategies refer to Table 2).

Factor that was changed	Resulting optimal chain
<i>Large scale gasification</i>	
Harvest costs of chips x 1.25	medium term strategy: months 2-5 instead of 3-5
Harvest costs of chunks x 1.25	short term strategy: months 1-3 instead of 1-2, long term strategy: harvest as stems instead of chunks
Forced drying costs x 1.5	medium term strategy: months 2-5 instead of 3-5
Thermal drying costs x 0.5	no change
Costs of chipping chunks x 2	no change
Transport distance x 2	no change
Natural drying rate 3%/month ^a	medium term strategy: months 3-9 instead of 3-5
Natural drying rate 7%/month ^a	long term strategy: months 5-12 instead of 6-12
MC requirements 0.4 ^b	medium strategy: months 2-3 instead of 3-5, long term strategy: months 4-12 instead of 6-12
<i>Small scale gasification</i>	
Harvest costs of chips x 1.25	medium term strategy: months 3-5 instead of 4-5
Harvest costs of chunks x 1.25	short term strategy: months 1-4 instead of 1-3
Forced drying costs x 1.5	medium term strategy: months 3-5 instead of 4-5
Costs of chipping chunks x 2	short term strategy: months 1-4 instead of 1-2, long term strategy: harvest as stems instead of chunks
Natural drying rate 3%/month ^a	short term strategy: months 1-4 instead of 1-3, medium term strategy: months 5-9 instead of 4-5
Natural drying rate 7%/month ^a	medium term strategy: months 2-4 instead of 4-5, long term strategy: months 5-12 instead of 6-12
MC requirements 0.4 ^b	long term strategy: months 4-12 instead of 6-12, no medium term strategy

^a standard 5% absolute/month: e.g. 50 to 45% equals 25 to 20%

^b required moisture content 0.4 instead of 0.25 kg water.(kg DM)⁻¹

The sensitivity analysis (Table 3) revealed that the supply strategies were robust because changing different factors in the supply chain had little effect on the strategies. Natural wind drying is of crucial importance because of its low cost. Basically, changing the assumptions only moved the transition points between short and medium term, and between medium and long term supply strategies. Exceptions are the cost increase of harvest as chunks for large scale gasification, and the cost increase of chipping for small scale gasification. In the latter cases, harvest as chunks is not feasible anymore and is replaced by harvest as stems. Although DM-

losses were not incorporated, the effect on the selected optimal design is probably small because this is not very sensitive to change.

Two changes in Table 3 require explanation. Firstly, natural wind drying rates were changed to investigate the effect on optimal chains of better or worse drying due to different weather conditions, different chunk pile dimensions and the effect of early harvest (i.e. December or January instead of February or March). Secondly, thermal drying costs were halved in order to incorporate the use of waste heat from the energy plant, but the optimal chain did not change. In this thesis, a rotary dryer was used. However, recent developments indicate that steam dryers and continuous fluid-bed dryers may be promising drying technologies for biomass fuels [Berghel and Renström, 1998]. Efficient thermal drying techniques and the use of waste heat can reduce the supply costs, but will not change the optimal strategies. It should also be noted that interest losses due to storage were not included in the cost calculations. Because supply chains were compared to each other as a function of time, interest losses are identical for options with the same time span between harvest and energy conversion. The inclusion of interest costs does not change the optimal chains, though it increases the actual supply costs.

In practice, specifications at the energy plant are not as strict as they are presented here. Furthermore, because practical experiences with biomass fuels are limited, fuel specifications at energy plants are not exactly clear and differences exist between plants. Optimal supply chains and associated supply costs largely depend on the local situation with respect to machinery, transport facilities, climatic conditions and so on. The optimization tool can handle these differences.

It is common practice that energy plants pay for the amount of dry matter delivered. The amount of dry matter slowly decreases due to DM-losses during storage and handling. Consequently, the value of the biomass stock slowly decreases. By choosing the right storage methods, both DM-losses and the moisture content can be reduced. A lower moisture content increases the net energy value and reduces the mass to be transported, gaseous emissions of the energy plant etc. Thus, it seems fair to reward willow suppliers for their efforts by paying for the amount of energy delivered corresponding to the gross amount of dry matter. Both the willow supplier and the energy plant will profit accordingly.

Overview

In this thesis, supply strategies and drying processes are described for willow biomass. The general trends of these supply strategies are likely to be valid for biomass fuels from other woody species, such as poplar coppice, prunings and trees like birch and pine. When biomass fuels of other woody species are harvested as

chips or chunks, results will be about the same as for willow, because the particle sizes are the same. However, to use the drying models described in this thesis, for other woody species, it may be necessary to investigate the drying characteristics. The supply costs may be different due to the need for different equipment (like harvesters).

Different supply strategies will probably occur when woody biomass is harvested as stems. Due to longer harvest cycles, stem diameters of poplar and other trees are usually much larger than those of willow. A larger stem diameter increases the time required for natural wind drying which means that, in practice, the moisture content can probably not be reduced as much as in willow. For whole trees of various wood species (Sitka spruce, pine), Gislerud [1990] reported that within one year a decrease in the moisture content to less than 0.33 to 0.5 kg water.(kg DM)⁻¹ was not possible. Thus, harvest as chunks may be preferable to achieve a larger reduction of the moisture content.

For fuel from non-woody species, such as miscanthus and hemp, supply chains may be completely different. In contrast to woody biomass fuels, the moisture content at harvest depends on the time of harvest [Huisman and Gigler, 1997]. In some cases, harvest can take place at a moisture content low enough for long term storage (e.g. harvest of miscanthus in March). It is also possible to apply field drying to reduce the moisture content of these crops [Huisman and Kortleve, 1994; Venturi et al., 1997]. However, for products like hemp and straw, the harvest period (which is from July until November) can also be a disadvantage for storage. From September onwards, ambient air conditions become less favourable, impeding drying. In order to enable the use of the drying models developed in this thesis (Chapters 3-5), investigation of the drying characteristics of non-woody biomass fuels is necessary. The optimization tool described in this thesis remains applicable.

Conclusions

The tool which was developed to optimize supply chains of willow biomass proved to be useful for deriving energy plant supply strategies. In this thesis, general supply strategies were derived for the situation in the Netherlands. However, the optimization model and drying models which were developed are suited for different input data, which means that these tools can be used for different (climatic and other) conditions.

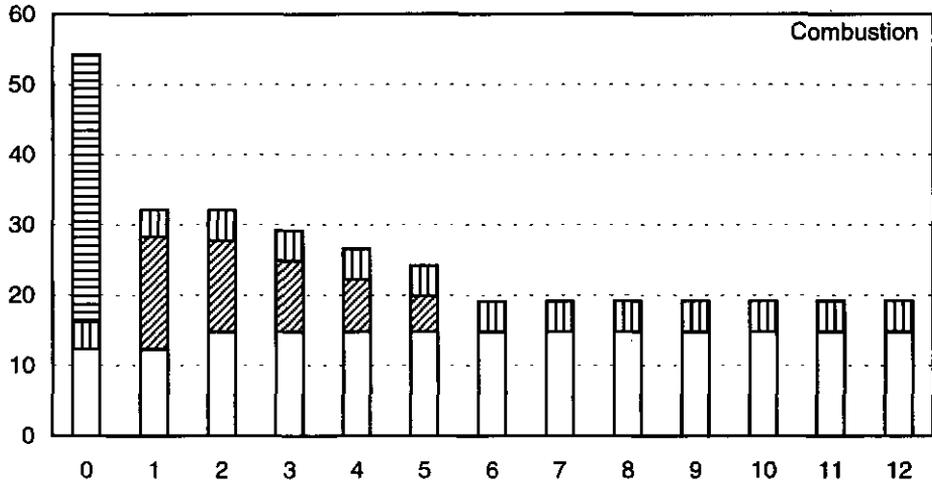
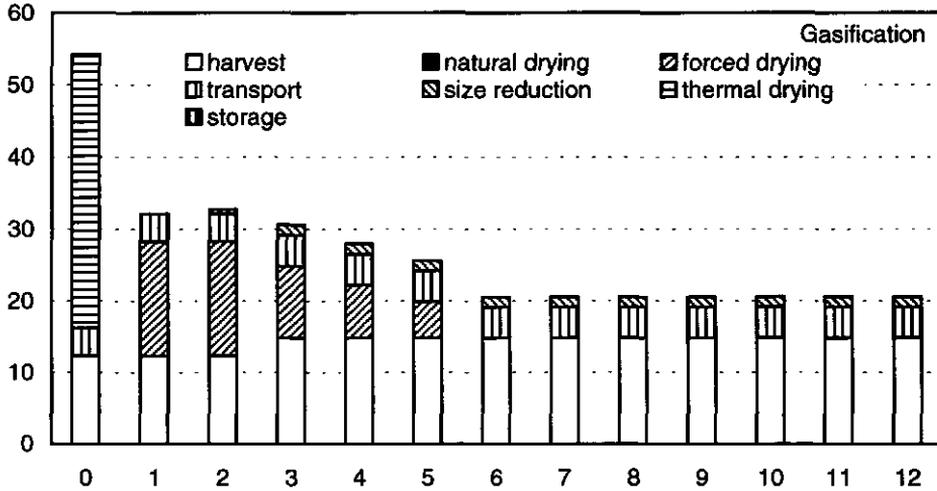
Regarding supply strategies, the time which is necessary to achieve the moisture content (specified by the energy plant) by natural wind drying is a determining factor as natural wind drying is a low cost method to reduce the moisture content. The following conclusions are drawn for the supply strategies:

- Supply of willow biomass to the energy plant immediately after harvest is not recommended. The willow fuel is too wet [approximately $1 \text{ kg water} \cdot (\text{kg DM})^{-1}$] and the time available for natural wind drying or forced convective drying is too short, which means that (expensive) thermal drying is necessary.
- If the time span between harvest and energy conversion is at least one month, but less than the time required to achieve the necessary reduction in the moisture content by natural wind drying; the best supply strategy is harvest as chunks, followed by natural wind drying at the farm and forced convective drying of chunks prior to transportation to the energy plant. Because the chunk pile dimensions can be used to influence the drying time, pile size should be adapted to the available time in order to reduce the moisture content as much as possible by cheap natural drying.
- If the time span between harvest and energy conversion equals or exceeds the time required to achieve the necessary reduction of the moisture content by natural wind drying; harvest as chunks or stems with natural wind drying at the farm prior to transportation is recommended.
- If necessary, size reduction can best be done at the energy plant as advantages of scale reduce the costs.

The supply strategies derived in this thesis can serve as guidelines for all parties involved in the process of generating energy from biomass.

Appendix I

Costs (EURO/t DM)

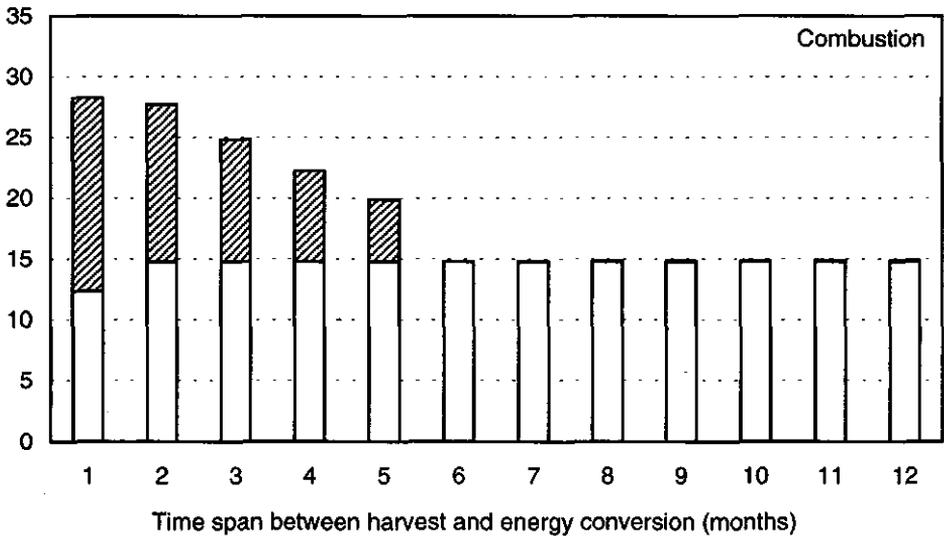
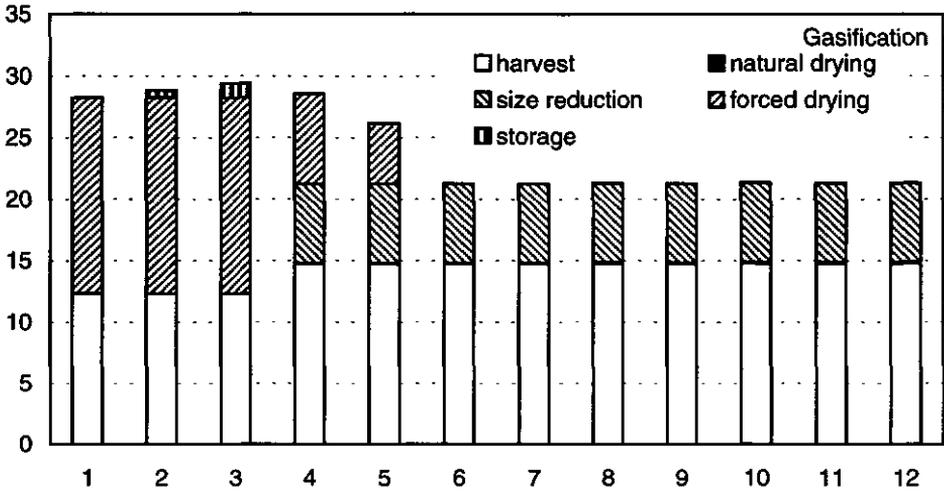


Time span between harvest and energy conversion (months)

Supply costs of willow as a function of the time span between harvest and energy conversion, for large scale gasification and combustion. For large scale gasification, harvest is as chips for months 0 to 2, from month 3 on as chunks. For large scale combustion, harvest is as chips for months 0 and 1, from month 2 on as chunks.

Appendix II

Costs (EURO/t DM)



Supply costs of willow as a function of the time span between harvest and energy conversion, for small scale gasification and combustion. For small scale gasification, harvest is as chips for months 1 to 3, from month 4 on as chunks. For small scale combustion, harvest is as chips for month 1, from month 2 on as chunks.

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Prompted by the need to reduce the output of CO₂ and other so-called 'greenhouse gases', renewable energy sources such as solar energy and biomass are gaining increasing notice. The Dutch Government has set a target to replace 10% of domestically consumed energy by renewable energy by the year 2020. Biomass is a collective noun for products of recent organic origin, which can be grouped into waste products (e.g. demolition wood, sewage sludge), by-products (e.g. straw, foliage) and energy crops (e.g. willow, poplar). A biomass fuel has a closed carbon cycle, and therefore is a renewable source of energy. At present, in the Netherlands, biofuels from energy crops are more expensive than from waste and by-products. If the price at which energy crops are offered can be reduced, they should attract more interest from energy producers. For agriculture, energy crops can be an alternative to common crops like grain, potatoes and sugar beet.

This thesis focuses on supply chains of biomass fuels to energy plants. As a representative of both woody biomass fuels and energy crops, willow (*Salix viminalis*) was chosen as the test sample. The objectives of the research were, *firstly*, to develop an optimization tool to determine minimum cost supply chains of willow biomass, *secondly*, to develop models to quantitatively describe the drying process of willow biomass and to investigate the parameters which govern this process, and *thirdly*, to provide general supply strategies which deliver willow biomass to energy plants (according to the plant's fuel specifications) at minimum costs.

The supply chain was defined as starting at harvest and ending at the energy plant. The supply chains considered consisted of harvest, storage, drying (natural, forced and thermal), size reduction and transportation. At harvest, willow has a moisture content of about 1 kg water.(kg DM)⁻¹. A lower moisture content is advantageous because it increases the conversion efficiency of willow, reduces gaseous emissions and enables long term storage of chips. At the energy plant, the fuel specifications are a moisture content of 0.25 kg water.(kg DM)⁻¹ and a particle size of chips or chunks. Thus, in the supply chain, drying and size reduction are necessary to meet the plant's fuel specifications.

To gain insight into the drying process, the drying characteristics of willow particles (chips and stems, with and without bark) were investigated. Drying processes were described with a diffusion equation for a plane sheet (chips) or for a cylinder (stems), linked to the mass transfer of moisture to the air. Drying of a willow stem with bark was successfully modelled as drying of a willow stem without bark surrounded by a thin layer (bark) with a much lower diffusivity. A willow stem with bark dried approximately ten times slower (drying time in the order of weeks) than a willow stem without bark (drying times in the order of days), due to the low diffusivity of the bark.

At bulk level, forced convective drying of chips and natural wind drying of stems were investigated. The bulk drying process was described with a deep bed drying model which accounted for the moisture and temperature gradients of both wood and air therein. The model was validated experimentally. Forced convective drying with ambient air of a 1 m high willow chip bed was adequately described by the model. The technical possibilities and costs of drying willow chips, using farm facilities for storage and drying of potatoes, were assessed, based on average monthly weather data. March to September was the most suitable period for drying due to favourable weather conditions. Compared to harvest costs, forced convective drying is a considerable cost factor in supply chains.

The natural wind drying process of willow stems in large piles was investigated. Data of large scale drying experiments were statistically analysed and compared to drying model calculations. During storage from harvest (December-April) until August, the average pile moisture content could be reduced from about 1.0 to between 0.2 and 0.3 kg water.(kg DM)⁻¹, which was close or equal to the equilibrium moisture content. The pile dried uniformly, except for the top layer which forms a small part of the pile only. Covering the pile had no long term effect on the moisture content. Within a single willow stem, the moisture content was largely uniform. Moisture diffusion within a stem was shown to be a long term process governed by the ambient relative air humidity and temperature. Evaporation of moisture at the outside of a stem was shown to be a short term process governed by rainfall, wind and global radiation.

Chunks combined the advantages of both chips and stems. Experiments and model calculations showed that chunks could be dried relatively quickly by forced convective drying and very cheaply by natural wind drying.

An optimization tool was developed to optimize supply chains of willow biomass by Dynamic Programming. The optimization model proved to be a useful tool in deriving supply strategies to energy plants. The model was applied to the situation in the Netherlands. The natural wind drying time, necessary to achieve the moisture content, specified by the energy plant, was a decisive factor in supply chains, because natural wind drying of chunks and stems is a low cost method to reduce the moisture content. A sensitivity analysis revealed that the supply chains were robust because changing different factors in the supply chain had little effect on the supply strategies. The following conclusions were drawn for the supply strategies:

- Supply of willow biomass to the energy plant immediately after harvest is not recommended. The willow fuel is too wet and the time available for natural wind drying or forced convective drying is too short, which means that (expensive) thermal drying is necessary.

- If the time span between harvest and energy conversion is at least one month, but less than the time required to achieve the necessary reduction in the moisture content by natural wind drying (up to around six months); the best supply strategy is harvest as chunks, followed by natural wind drying at the farm and forced convective drying of chunks prior to transportation to the energy plant. Because the drying time of chunks can be influenced by the pile dimensions, pile size should be adapted to the available time in order to reduce the moisture content as much as possible by cheap natural drying.
- If the time span between harvest and energy conversion equals or exceeds the time required to achieve the necessary reduction of the moisture content by natural wind drying (from around six months on); harvest as chunks or stems with natural wind drying at the farm prior to transportation is recommended.
- If necessary, size reduction can best be done at the energy plant, since advantages of scale reduce the costs.

These supply strategies can serve as guidelines for all parties involved in the process of generating energy from biomass.

Samenvatting

Drogen van wilg in aanvoerketens van biomassa

De belangstelling voor duurzame energie (zoals zonne- en windenergie en energie uit biomassa) neemt wereldwijd toe. De belangrijkste reden is dat door het vervangen van fossiele brandstoffen (aardolie, aardgas en steenkool) door duurzame energiebronnen de uitstoot van koolstofdioxide afneemt. Zodoende kan het broeikas-effect, waardoor de temperatuur op aarde langzaam stijgt, worden tegengegaan. De Nederlandse overheid heeft zich als taak gesteld om in het jaar 2020 10% van onze energie duurzaam op te wekken.

Biomassa is organisch materiaal dat als brandstof in een energiecentrale kan dienen. Er worden drie stromen onderscheiden, namelijk afvalproducten (bijv. bouwen sloophout), bijproducten (bijv. stro en loof) en energiegewassen (bijv. wilg en populier). Als brandstof staan momenteel in Nederland vooral afval- en bijproducten in de belangstelling omdat ze goedkoper zijn dan energiegewassen. Echter, door verlaging van de prijs van energiegewassen kan de belangstelling van energieproducenten voor deze brandstof toenemen. In de toekomst is dit mogelijk interessant voor de landbouw, omdat energiegewassen een alternatief kunnen bieden voor gangbare gewassen als aardappelen, bieten en granen waarvan de prijs steeds onder druk staat.

Eén van de mogelijkheden om de prijs van energiegewassen te verlagen is de aanvoer van biomassa naar een energiecentrale goedkoper maken. Daar richt dit proefschrift zich op. Als voorbeeld is het energiegewas wilg (*Salix viminalis*) gekozen. Alle handelingen die nodig zijn om wilg van de plaats van de oogst naar de energiecentrale te brengen, worden tezamen de *aanvoerketen* genoemd. De aanvoerketen bestaat hier uit de volgende schakels: oogst, opslag, drogen, verkleinen en transport. De aanvoerketen eindigt bij de energiecentrale waar de brandstof aan de eisen van de centrale moet voldoen.

De oogst van wilg kan als chips, blokjes (ofwel chunks, die groter zijn dan chips) of hele stengels plaatsvinden. Tijdens de oogst is het vochtgehalte van wilg ongeveer 50%. In dit proefschrift wordt verondersteld dat de energiecentrale een vochtgehalte van ongeveer 20% en een deeltjesgrootte die overeenkomt met chips of blokjes nodig heeft. Verlaging van het vochtgehalte heeft als voordeel dat meer energie uit biomassa wordt gehaald, minder schadelijke rookgassen worden uitgestoten en dat de opslag van droge wilgenchips gedurende lange tijd mogelijk is. Voor het drogen wordt onderscheid gemaakt tussen natuurlijk (door de wind), geforceerd (met een ventilator) en thermisch drogen (met hete lucht).

De doelstelling van dit proefschrift is driedelig. De drie delen worden hierna beschreven.

Eerste doelstelling: het ontwikkelen van een optimalisatiemodel waarmee de goedkoopste aanvoerketen van biomassa naar een energiecentrale kan worden berekend.

Het optimalisatiemodel dat in dit proefschrift is beschreven, is gebaseerd op de wiskundige techniek 'Dynamische Programmering'. Het optimalisatiemodel is een handig hulpmiddel om voor verschillende situaties op een snelle manier de goedkoopste aanvoerketen te bepalen.

Tweede doelstelling: het ontwikkelen van modellen die het drogen beschrijven en het onderzoeken van de factoren die van invloed zijn op het drogen.

Het droogproces van wilg is op twee niveaus onderzocht: losse deeltjes en een heel bed met deeltjes. Op deeltjesniveau zijn chips en stengels (met en zonder bast) onderzocht. Het droogproces is beschreven met een diffusiemodel voor een vlakke plaat (voor chips) en voor een cilinder (voor de stengels). Een stengel met bast is beschreven als een stengel zonder bast, omgeven door een dunne laag (de bast) met een hoge weerstand tegen uitdrogen. Een stengel met bast droogt ongeveer 10 keer zo langzaam (in de orde van weken) als een stengel zonder bast (in de orde van dagen).

In een heel bed met deeltjes is het geforceerd drogen van wilgenchips (met een ventilator) en het natuurlijk drogen van wilgenstengels (aan de wind drogen) onderzocht. Het drogen in een bed is beschreven met een model dat rekening houdt met het vochtgehalte en de temperatuur van het hout en van de drooglucht (een zogenaamd 'diep bed' model). Met wilgenchips zijn experimenten uitgevoerd waarbij een bed met een hoogte van 1 m werd gedroogd. Het model beschreef het drogen goed. Verder zijn de mogelijkheden en kosten onderzocht om wilgenchips in een aardappelschuur te drogen onder Nederlandse weersomstandigheden. Het bleek dat de periode maart-september het meest geschikt was maar dat de kosten van het drogen van wilgenchips in vergelijking tot de oogstkosten (te) hoog zijn.

Met het natuurlijk drogen van wilgenstengels tijdens opslag in grote stapels zijn ook experimenten uitgevoerd. Gedurende opslag vanaf de oogst (december-april) tot en met augustus daalde het vochtgehalte van ongeveer 50% tot 10 à 20%. Het model voorspelde het drogen correct. Verder bleek dat de verdeling van het vochtgehalte in de stapel uniform was, op de toplaag na. De toplaag vormt echter maar een klein deel van de stapel en heeft daarom weinig invloed op het gemiddelde vochtgehalte van de stapel. Afdekken van de stapel tegen regen had op de lange termijn geen nut. Binnen een stengel was het vochtgehalte ook min of meer uniform. Transport van water binnen een stengel is een heel langzaam proces. Dit proces

hangt af van de relatieve vochtigheid en temperatuur van de lucht. Het verdampen van water aan de buitenkant van een stengel is een relatief snel proces dat afhankelijk is van neerslag, wind en zonnestraling.

Blokjes combineren de voordelen van chips en stengels. Experimenten en berekeningen met het droogmodel toonden aan dat blokjes snel geforceerd drogen en dat natuurlijk drogen een goedkoop alternatief is.

Derde doelstelling: het afleiden van een algemene strategie waarbij wilg tegen zo laag mogelijke kosten aan de centrale wordt geleverd.

Uit de berekeningen met het optimalisatiemodel (eerste doelstelling) blijkt dat de tijd die beschikbaar is voor natuurlijk drogen zeer belangrijk is, omdat natuurlijk drogen goedkoop is. De conclusies zijn als volgt:

- Aanvoer van wilg naar de energiecentrale *onmiddellijk* na de oogst is niet aan te bevelen omdat de brandstof te nat is. De tijd om (goedkoop) natuurlijk en/of geforceerd te drogen is dan te kort. De enige mogelijkheid is thermisch drogen hetgeen te duur is.
- Wanneer de beschikbare tijd ten minste één maand bedraagt, maar niet genoeg is om met natuurlijk drogen het gewenste vochtgehalte te bereiken (ongeveer 6 maanden), dan is de beste strategie: oogst als blokjes, gevolgd door natuurlijk drogen en geforceerd drogen op de boerderij, waarna transport naar de energiecentrale kan plaatsvinden. Door de diepte van de blokjesstapel aan de beschikbare tijd aan te passen, kan de droogtijd worden beïnvloed: hoe meer tijd beschikbaar is, hoe dieper de stapel mag worden.
- Wanneer de beschikbare tijd voldoende is om het gewenste vochtgehalte met natuurlijk drogen te bereiken, is de beste strategie: oogst als blokjes of stengels, gevolgd door natuurlijk drogen en vervolgens transport naar de energiecentrale.
- Indien nodig kan verkleinen van stengels en blokjes tot chips het best bij de energiecentrale worden gedaan omdat daar de kosten vanwege schaalvoordelen het laagst zijn.

Alhoewel elke situatie anders is, zijn de algemene aanvoerstrategieën, zoals hierboven beschreven, als richtlijnen te gebruiken door alle partijen (bijv. brandstofleveranciers, energieproducenten en transportbedrijven) die bij het proces van energieopwekking uit biomassa betrokken zijn.

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Jörg

Curriculum Vitae

Jörg Klaus Gigler was born in Gangelt, Germany, on 14 March 1967. In 1987, he completed secondary school at the Bisschoppelijk College in Sittard, the Netherlands. In the same year, he started with his studies in Agricultural Engineering at Wageningen Agricultural University (WAU, since 1999 Wageningen University). He conducted a MSc. project on greenhouse climate control at the Department of Agricultural Engineering and Physics (WAU). He also conducted a MSc. project on simulation of ground pressure distribution under tracked vehicles at the Department of Agricultural and Food Engineering, University College Dublin, Ireland. As part of his studies, he spent a practical training period of eight months on farm implements for animal traction at the Palabana Animal Draft Power Development Programme, Zambia. In August 1993, he obtained his MSc. degree. From June 1994 until May 1999, he worked at the Institute of Agricultural and Environmental Engineering (IMAG) in Wageningen as a researcher on biomass energy. From 1996 onwards, he conducted the research described in this PhD thesis. In 1998, he also worked part-time for the Netherlands Agency for Energy and the Environment (NOVEM). In 2000, he will spend one year as a post-doctoral fellow at the Centre for Energy Research, Massey University, New Zealand.

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