Technology Characterisation for Natural Organic Materials

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1. Introduction

Today most energy scenario models only take energy efficiency measures and changes in energy resources into account. However, a large part of the energy consumption is associated with the production of materials. The MATTER-study aims to optimize both the energy and the material flows in Europe in one model. The MARKAL model, a linear optimization model, is used for this purpose. Different Dutch institutes are involved in the project (Bureau B&G, Universities of Groningen and Utrecht and the Free University of Amsterdam. The project is coordinated by the Netherlands Energy Research Foundation ECN. The material flow modeling is divided in the material groups: plastics, natural organic materials, ceramic and inorganic materials and steel. Furthermore three product groups are discerned: packaging, transport and buildings.

This report deals with the production process data (costs and energy efficiency) of natural organic materials: wood products and pulp and paper products. For every production process of the different forest products a description of the process will be stated, followed by the process data.

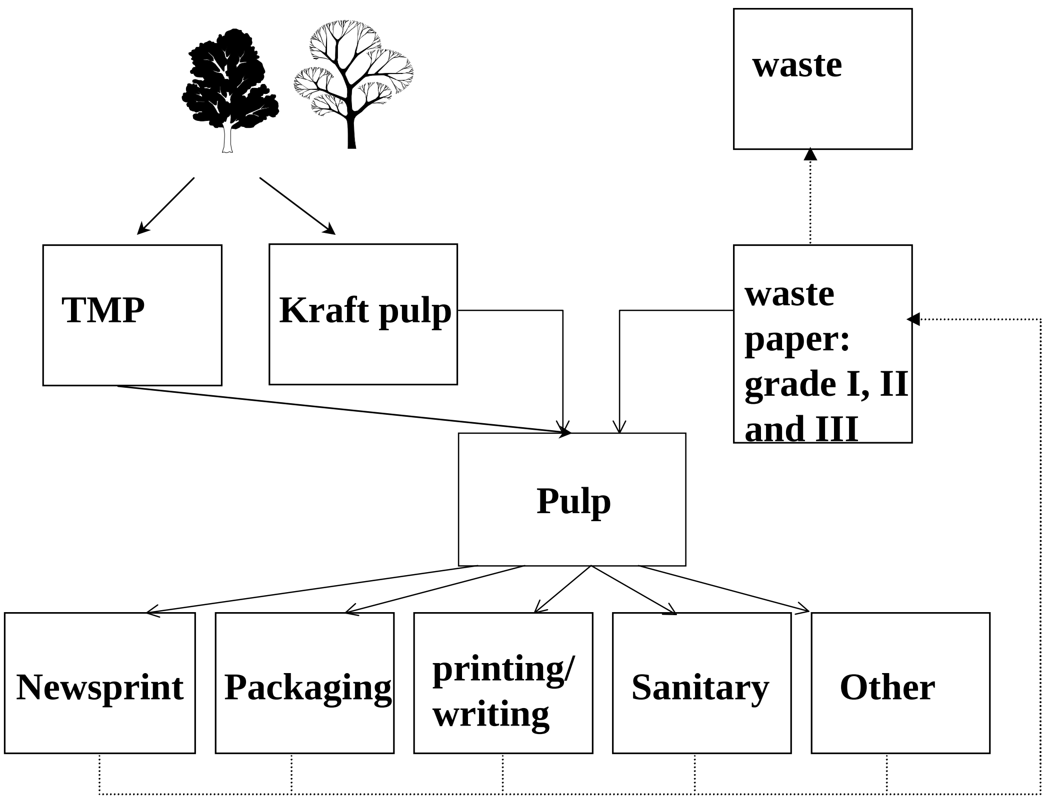
2. System boundaries and methodology

In the Markal model both the paper cycle and the wood cycle will be modeled. Modeling the production of different paper products is fairly complicated. Depending on the desired quality, different inputs are required like chemical pulp, mechanical pulp, and waste paper. The paper products can be produced in an integrated pulp and paper mill or in separate pulp and paper mills. Depending on the quality of the paper products different qualities of waste paper can be recovered in the waste stage. To deal with all these factors the system as depicted in Figure 1 will be modeled in Markal.

Figure 2.1 deals with non-integrated mills and shows that pulp is used as feedstock for every paper production process. Depending on the desired paper quality the type of pulp that is used will differ. 5 pulp types will be modeled: Thermomechanical pulp, chemical pulp and three waste paper pulp qualities (grade I: deinked waste paper graphical paper making, grade II: deinked waste paper for newsprint making, grade III: non-deinked low quality waste paper pulp for board making.). To model alternatives for current pulping technologies and resource use we will also describe pulping processes that make use of enzymes and pulping processes that use non wood resources as feedstock.

For paper making, we assumed that the energy requirements and the production costs of the paper mill are not affected by the pulp type that is used in the process. For every paper type a pulp mixture can be used based on the 5 main pulp types that are modeled. The Markal model is free to determine the pulp input within bounds that are set in the tables that describe the production processes. For example the share of waste paper pulp input will be restricted to minimum and maximum bounds for each paper grade for different target years. The target years are 2000, 2020 and 2050. Furthermore we defined an integrated pulp and paper mill for every paper product that is modeled. All integrated mills use 100% virgin wood as feedstock. For the integrated Newsprint mill data were available, however for the other integrated mills no specific data per paper product were available. For every paper product we modeled an integrated mill based on the non-integrated process. We assumed that the difference in energy consumption between integrated and non-integrated mills is the result of the pulp drying that is necessary for non-integrated mills. Integrated mills can use the energy normally needed for pulp drying for the paper drying process. According to Nilsson (1995) 27% of the steam consumption in a Kraft pulp mill is needed for pulp drying while 17.5% of the electricity consumption is used in this process. The energy demand of an integrated mill is calculated by adding the energy consumption of the paper mill and the pulp mill and extracting the energy demand for pulp drying.

Figure 2.1: system for modeling of paper production with non-integrated mills



For the modeling of wood products back loops also have to be taken into account. Old wood can be used for the production of different types of wood based panels and several techniques are available to create large beams from small pieces of wood. No information is available on the desired qualities of old wood or waste wood to produce panels or other engineered wood products. In the tables that describe the production of the wood products, the input of waste wood or old wood is taken into account but no quality is modeled. We modeled 5 wood types: sawnwood (hard wood and soft wood), particleboard, plywood, OSB, and Glulam.

We modeled different wood based panel types because they differ in resource use and energy consumption during production. Many wood based panels can be used for similar applications but special characteristics can make one panel more suitable for a certain application than the other. This is another reason for modeling more than one wood based panel type.

We modeled two sawnwood types because sawn hardwood and softwood differ a lot when the resources are taken into account. Softwood that is harvested in Europe often comes from plantations that are renewable. This means that the harvested wood has a neutral CO_2 balance (the CO_2 emitted at the end of the lifetime of a wooden product is sequestrated by the new tree planted). Even though European softwood may be renewable, it does not mean that it is also sustainable. In order to be sustainable the forests need to meet some other criteria too like forest health and vitality, biological diversity, soil and water conservation, multiple forest functions and socio-economic benefits [Parviainen, 1995].

For hardwood we can differentiate between hardwood from temperate forests and tropical forests. The total temperate forest area is currently stable or increasing but the regional losses in developing countries are a problem [Dudley, 1992]. Deforestation of the tropical forests takes place at a large scale which is considered a very large problem due to the loss of enormous rich pools of genetic resources and the loss of soil fertility [Lamprecht, 1989]. It is estimated that the loss of tropical forests in the 1980ies amount to 1.5% of the total amount of tropical forest area [Bulte and van Soest, 1995]. The use of tropical hardwood is not only unsustainable from a CO_2 point of view but also from other environmental and social reasons.

The only environmental aspect that the MARKAL model focuses on is the emission of CO_2. For this reason the only important criteria is that a forest is renewable or not. Therefore we differentiate between hardwood and softwood where the use of softwood is associated with lower CO_2 emissions than the use of hardwood. It is not an easy task to determine the CO_2 emission related to the use of wood. The extremes are not difficult to determine (If wood would not be renewable at all (in case of clear cutting practices) all CO_2 that is sequestrated in the wood should be taken into account. On the other hand if forest management is focused on replanting after felling of trees, no sequestrated CO_2 should be taken into account) but the actual situation depends strongly on the region from which the wood is imported. For modeling in MARKAL choices have to made about working with the extremes or trying to determine more specific

Softwood and hardwood also differ in the possible applications for which they can be used. Hardwood is generally more 'durable' than softwood and therefore easier to use in outdoor applications where the weather has a negative effect on the lifetime of the wood. Softwood can be made more durable by means of wood preservation techniques. We will not model these techniques because the effects on the environment are not related to CO_2. Most effects are related to the use of heavy metals (copper, chromium, arsenic) and creosote. Lately some techniques are developed that change the structure of softwood and thereby making it more durable. These techniques are called wood modification. We will model one wood modification process, the PLATO process, in order to make it possible for the model to use softwood for durable use in outdoors applications. The effects of the PLATO process to the environment are restricted to energy use and therefore suitable for modeling with the MARKAL model.

3 Production of wood products

In 1991 the Western European sawnwood consumption was 91 million m^3. Another 41 million m^3 of wood based panels was consumed [FAO, 1993]. The FAO projects that the consumption of wood products will increase dramatically. The projected European consumption of sawnwood in 2010 is expected to reach 255 million m^3 and the wood based panel consumption is expected to increase to 117 million m^3 in 2010.

Worldwide, 51% of the wood consumption is used as fuel, 32% is used as construction wood and 9% is used as pulpwood for paper production. The other 8% is can be categorized as ‘other consumption’[FAO, 1993].

The following sections will on 5 types of wood products: sawnwood (softwood and hardwood), particle board, plywood, OSB and Glulam. We did not take industrial roundwood into account even though the European consumption was almost 300 million m3 in 1991 [FAO, 1993]. This was done because roundwood is used for the production of both sawnwood and wood based panels which are already described. Furthermore hardly any energy is used in the production of roundwood. Roundwood also contains the categories fuelwood, pulpwood, chips and wood residues.

3.1 The production of sawnwood

The sawmilling industry

The sawmilling industry in Europe is characterized by a large number of mills with a relative small production capacity. The mills are often under capitalized and therefore unable to install the latest improvements in process technology (notably computer control). It is estimated that in 1990 there were about 30,000 sawmills in Europe with a total production capacity of 85 million m^3 per year [UN-ECE, 1996]. The average production capacity is therefore less than 3000 m^3 per mill per year.

A large part of the total European production is produced by a few large mills. In 1990 there were about 80 mills producing over 100,000 m^3 per year. 59 of these mills were located in Austria (1), Finland (27) and Sweden (21) [UN-ECE, 1996].

We differentiate two types of sawnwood, namely sawnwood produced from hardwood (Table 3.1) and sawnwood produced from softwood (Table 3.2). The production of sawnwood from softwood in Europe is higher than the production from hardwood (59 million m^3 and 11 million m^3 respectively in 1990) [UN-ECE, 1996].

The process for the production of sawnwood is basically very simple. After the trees are cut down the wood is debarked. The wood is then sawn and dried, either naturally or forced.

Energy consumption of sawmills

Several studies have dealt with the production of sawnwood in relation with energy use. First of all, van Heijningen (1992) did research about the gross energy requirements of sawn wood. In van Heijningen (1992) a large difference in energy use is stated between the production of hardwood and softwood sawn lumber. The reason for this is that the drying of hardwood uses more energy for drying (3,0 GJ_{prim} versus 0.3 GJ_{prim}) [van Heijningen, 1992]. Besides these heat requirements van Heijningen (1992) states a electricity requirement of 0.77 GJ_{el} for both hardwood and softwood.

In Richter and Sell (1992) energy data for several wood products are stated based on the Swiss situation. According to them 2.8 GJ_{prim} is needed for drying of one ton sawn softwood. Furthermore 0.78 GJ_{el} is needed for sawing. Due to energy requirements during logging and transport the total primary energy requirement for the production of sawn softwood is 3.77 GJ/ton [Richter and Sell, 1992, Richter, 1993]

In Frühwald (1997) the energy consumption for the production of sawn softwood timber is estimated at 417 MJ_{prim} per m3 (360 MJ_{prim} electricity and 57.4 MJ_{prim} diesel. This corresponds to 1.11 GJ_{prim} per ton (Frühwald uses a density of 377 kg per m3 for softwood). This low figure is due to the fact that these figures are relevant for timber that is not dried. The drying stage consumes 5.3 GJ_{prim} per ton [Frühwald, 1997]. Assuming a boiler efficiency of 80% the process uses 4.2 GJ steam.

For the energy data in the Table 3.1 and 3.2 we have combined the data from van Heijningen (1992), Frühwald (1997) and Richter and Sell (1992).

Van Heijningen seems to be on the low side for the drying stage. We will use the data from Frühwald for the drying of hardwood and the Richter and Sell (1992) data for drying of softwood. These data correspond well with data in Eichhammer et al. (1997). In Eichhammer et al. (1997) it is also stated that the variation in energy consumption for drying is significant due to factors like:

- the initial water content of the timber
- required final water content
- degree of heat recovery
- degree of insulation

The electricity demand stated by van Heijningen (1992) and Richter and Sell (1992) match very well. We will use this figure for the electricity demand. In the Tables 1 and 2 we expressed all inputs in 100% dry matter. In reality however the water content of primary wood is about 49% while the water content of sawnwood is about 10%.

The transportation distance from the logging site to the sawmill for softwood varies between 25 km for small sawmills and 160 km for large (>10.000 m3/yr) mills in Germany. The average transportation distance for hardwood is 70 km in Germany [Frühwald, 1997].

Costs of sawmilling

Earlier in this chapter we described that the sawmilling industry consists of many small sawmills. This is possibly the reason for lack on cost data in literature. We will therefore estimate the costs of sawmilling based on the market prices of sawnwood.

The international market prices of sawnwood can either be derived from import or the export figures. Prices that are calculated by using financial and quantitative import data are most of the times higher than using export data. The ITTO (International Tropical Timber Organization) uses export data for their estimates of tropical hardwood prices in various countries[1].

We determined the weighted average prices of sawnwood in Europe by studying the export quantities in physical and financial units in the largest European exporting countries (Germany, France, Sweden, Finland, Hungary and Norway).

The average export price for coniferous sawnwood in 1995 is \$241 per m^3. The prices varied between \$201 and \$251 per m^3 [FAO, 1997].

The prices do not represent the production costs of sawnwood because the material input costs need to be subtracted from the price data in order to make a decent estimate. The prices for coniferous roundwood are calculated at \$76 per m^3 [FAO, 1997]. Finally we need to take production losses into account. In de Boer (1995) production losses at sawmilling are estimated at 40% of the wood input. This results in a material input cost of \$127 per m^3 sawnwood output. These production losses can be sold on the market as chips, particles and residues. The prices of these products are about \$33 per m^3 and therefore \$24 per m^3 sawnwood output.

The data stated above lead to a total cost of \$138 or ECU 125 per m^3 sawnwood output. If we follow the same calculations for hardwood the costs are determined at \$240 or ECU 218 per m^3. The total material input is calculated at 171 ECU per m^3 output. The higher production costs can be explained by greater drying times and the fact that better equipment and more labor hours are needed to produce a product with a higher value added. Because sawmills are light industries and not very capital intensive we assume that the O&M share in the total costs are twice the share that we use for heavy industry (5%). The labor costs are assumed to twice the share that is common in the wood based panel industry; the latter is estimated at 20% based on Gov. Canada (1997).

[1] As stated in ITTO's Tropical Timber Market Report published at http://.itto.or.jp

To indicate the investment costs when the total production costs are known we assume an economic lifetime of the sawing technology of 10 years and an interest rate of 10%. This results in an annuity factor of 0.16[2]

In Table 3.1 and 3.2 the energy and cost data are listed for sawn softwood and hardwood. An availability factor of 0.8 is assumed because many sawmills are only working during the harvest season [FAO, 1997]. The data in Table 3.1 and 3.2 are stated per ton output. We used average wood densities of 650 kg per m^3 for hardwood and 500 kg per m^3 for softwood.

Table 3.1, Technology characterization of sawing of hardwood

	2000	**2020**	**2050**
Input Resources (tonne)			
hardwood	1.6	1.6	1.6
Output (tonne)			
sawn hardwood	1	1	1
saw dust	0.6	0.6	0.6
Energy consumption (GJ/ton)			
Fuel	5.3	5.3	5.3
Electricity (GJe/ton)	0.77	0.77	0.77
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	1108	1108	1108
O&M	168	168	168
o.w labor	134	134	134
transportation (km)	70	70	70
references	van Heijningen, 1992 Frühwald, 1997	FAO, 1997 Richter and Sell, 1992	

[2] $\alpha = r/(1-(1+r)^{-n}$ where r = interest rate, n = depreciation period and α = annuity factor).

Table 3.2, Technology characterization of the production of sawing softwood

	2000	2020	2050
Input Resources (tonne)			
wood	1.6	1.6	1.6
Output (tonne)			
sawn softwood	1	1	1
saw dust / other wood waste	0.6	0.6	0.6
Energy consumption (GJ/tonne)			
fuel	2.8	2.8	2.8
Electricity (GJe/ton)	0.77	0.77	0.77
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	833	833	833
O&M	125	125	125
o.w labor	100	100	100
transportation (km)	70	70	70
references	van Heijningen, 1992 Frühwald, 1997	FAO, 1997 Richter and Sell, 1992	

3.2 The PLATO process

In the previous paragraph a distinction is made between sawn hardwood and softwood. In general hardwood has a longer lifetime than softwood. Many wood preservation techniques however are available to upgrade the lifetime of softwood. Many of these techniques are based on impregnation of chemicals into the wood structure. These preservation methods are not modeled for the MARKAL model because the effects on the environment are not related to energy consumption or CO_2-emission. The environmental effect are caused by the chemicals used in the process that are somewhere during the lifetime of the wood released into the environment.

One process that is still in the development phase does not use chemicals to extend the life time of wood but uses steam and high pressures to modify the wood structure and thereby extending the lifetime. This process is called PLATO (Providing Lasting Advanced Timber Option) and is originally developed by SHELL. Now Cr&do in Wageningen, The Netherlands, is developing and testing this process.

In the Markal model this process can be used to upgrade softwood timber to hardwood quality. By modeling this process we need to take into account that the comparison of softwood and (tropical) hardwood involves much more criteria than CO_2-emission.

Plantations of softwood in Scandinavia may be sustainable from a CO_2 point of view but may score totally different when biodiversity aspects are taken into account. Furthermore the sustainability of tropical hardwood use is depends heavily on the harvest methods that are used.

According to Fraanje (1998) the energy consumption is 740 MJel. and 420 MJth per m3 poplar PLATO wood produced. Characteristic for the PLATO process is that the density of platonised wood is higher than the original wood. The increase in density depends on the process used (PLATO-light and PLATO-heavy). We will assume an average density of 1 tonne per m^3. No investment costs are available for this process.

3.2 The production of particleboard

The particle board industry

The particle board industry is the largest industry compared to the other industries that produce wood based panels. In 1990 the total production of wood based panels amounted to 30 million m^3 and the production of particle board was 24.4 million m^3.

In the last 30 years the consumption of wood based panels more than doubled. The growth rate in the period 1964 - 1973 was almost 10% per year. In the following period toll 1989 the average growth was much lower (2.5% per year) and the current growth rates are only about 0.2%. The reason for this trend is that in the sixties wood based panels started to be a substitute for sawn wood in existing markets. Today the market has become a mature market similar to the one for sawnwood [UN-ECE, 1996]. The production of wood based panels in Europe is only slightly less than the consumption (30 and 34 million m^3 respectively). For particle board production and consumption are exactly balanced [UN-ECE, 1996].

The wood based panel industry consists of approximately 800 plants with a total capacity of nearly 50 million m^3 . The average plant sizes are much larger than sawmills. The particle board plants are the large compared to the rest of the wood based panel industry. The average size is around 150 thousand m^3 per year while veneer and plywood plants have an average capacity of about 10 thousand m^3. Fiberboard plants have an average capacity of little more than 70 thousand m^3 [UN-ECE, 1996]

The largest producers of particle board in Europe in 1991 were Germany (7.4 million m^3), France (2.6 million m^3), Italy (3.0 million m^3) and Belgium-Luxembourg (2.3 million m^3) [UN-ECE, 1993].

Particleboard consists of small wood parts that are glued together under high pressure. Most of the raw material is low quality wood that is not used by other wood processing industries, like chipped thinnings and sawmill waste. Also clean demolition wood is used in the production process [Renia and Sikkema, 1991]. All the wood is chipped and dried.

The wood chips are mixed with glue and pressed between two hot plates. After pressing the panels are sawn and sanded. In the process both electricity and oil is used [van Heijningen, 1992].

Energy consumption in the particle board industry

Van Heijningen (1992) estimates the energy consumption for the production of particleboard at 2.8 GJ fuel and 0.6 GJ_{el} electricity per ton.

In Richter and Sell (1992) different energy requirements are stated for the production of particle board. They estimate the total primary energy requirement at 6.5 GJ_{prim}/ton. In [Frühwald, 1997] energy data are presented for the production of particleboard that are based on the experience of 10 particleboard manufacturers in Germany. For the production of 1 m3 (734 kg) particleboard 1274 MJ_{prim} electricity and 1429 MJ_{prim} steam is needed. For the production of steam mainly wood is used as an energy source (1072 MJ_{prim}). These figures correspond to 1.7 GJ_{prim} electricity (corresponds to 0.34 GJ_{el} per ton assuming an efficiency of 20%) and 1.95 GJ_{prim} steam per ton.

The figures stated by Frühwald (1997) differ from the figures stated by van Heijningen (1992) and Richter and Sell (1992). A possible reason for these differences is that Frühwald (1997) uses more up to date data than the other sources. We'll use the Frühwald data as an estimate for the average European situation in 2000.

Besides electricity and steam for the production process, also energy is needed for the production of glue. In van Heijningen it is stated that the production process of particle board uses about 67 kg glue per ton output with an energy input of 80 GJ/ton [van Heijningen, 1992]. This means that 5,4 GJ is needed for the production of glue per ton particle board. The Büro für Umweltchemie (1995) estimates a glue input of around 9% and a differentiation is made between several glue types (Phenol-formaldehyde, Urea-formaldehyde and polymeric Isocyanate). The energy requirements in the production of these adhesives varies between 73.3 GJ/ton and 138 GJ/ton. Frühwald estimated the average glue input at 62 kg adhesives per m3 particleboard [Frühwald, 1997]. Richter and Sell (1992) estimate an energy consumption for adhesive production at 3.9 GJ_{prim}/ton particle board.

Based on the figures stated above it seems reasonable to use the van Heijningen (1992) figure, 5.4 GJ per ton particleboard as an estimate. This energy demand is not added to the energy figures in table 3.3 but should be used as input data in the Markal model.

According to Renia and Sikkema (1991) about 68% of the total input of German particle board mills consists of by-products from the wood processing industry. The shares of different feedstock for particleboard production are as follows: 38% is virgin wood parts, 29% is old wood, 16% is sawdust, 11% is wood particles and 7% is sawing waste. These figures can be seen as representative for Europe because 30% of the total European particle production takes place in Germany [Renia and Sikkema, 1991].

The average transportation distance for the input material to reach the particle board mill is estimated at 1000 km by Frühwald (1997). This large transport distance is probably the result of international transport of the wood byproducts.

Costs of particle board production

To estimate the costs of particle board production we follow the same method as for the sawnwood cost estimates.

The average export price of particle board is \$290 per m^3 or ECU 264 per m^3 . The input for particle board production consists mainly of wood from the category: chips, parts and residues with an average price of ECU 30 per m^3 or ECU 39 per m^3 output of particle board. We estimate the glue costs to be the about the same level.

This leaves a production cost of ECU 200 per m^3 which corresponds with EN-ECE (1996) which states that the costs of producing wood based panels are about the same level as for sawmilling.

Contrary to sawmills the particleboard industry is a very capital intensive and high technology industry [UN-ECE, 1996]. Most of the costs of the production process are therefore likely to be related to the investments and a smaller part to labor and other variable costs. We will therefore assume that O&M account for 5% of the total production costs. Labor costs are assumed to account for 20% of the production costs [Gov. Canada, 1997]. We assumed an availability level of 90%.

Table 3.3, Technology characterization of the production of particleboard

	2000	2020	2050
Input Resources (ton/ton)			
wood (chips)	1	1	1
adhesives	0.07	0.07	0.07
Output (tonne)			
particle board	1	1	1
Energy consumption (GJ/ton)			
heat	1.95	1.95	1.95
Electricity (GJe/ton)	0.34	0.34	0.34
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	1389	1389	1389
O&M	50	50	50
o.w labor	40	40	40
transportation (km)	1000	1000	1000
references	van Heijningen, 1992	Frühwald, 1997	Richter and Sell, 1992

3.3 The production of plywood.

The plywood industry

The production capacity for plywood production in Europe in 1994 amounted to 3.8 million m^3. The total number of production plants in 1994 was 325 which results an average production size of 11.7 thousand m^3. This is relatively low compared for example the particle board industry (150 thousand m^3). The plywood production accounts for 8% of the total European production capacity of wood based panels [UN-ECE, 1996].

Plywood is a wood based panel that consists of multiple layers veneer. To produce veneer sheets, logs are rotated around their length axis against a knife, which peels thin layers of wood from the log. The veneers are then dried and glued together in such a way that its grain direction is at right angles to that of the adjacent layer. The last step is hot pressing of the panels. Prior to hot pressing many mills pre-press assembled panels with a cold press [Moavenzadeh, 1990].

The production of plywood leads to a lot of waste (hogfuel/wood waste), approximately 24% [van Heijningen, 1992, Forintek, 1993]. Besides plywood and waste some other co-products are produced in the process. In Table 3.4 we assume a net input of fresh roundwood of 2.2 tons (50% moisture) per ton of plywood (moisture content of 12%) which is 1.4 tonne per tonne output when expressed in 100% dry matter.

Energy consumption in the plywood industry

Steam is used throughout the production process. About 30% is used for log conditioning, 55% is used for veneer drying and 10% is used for hot pressing. The last 5% is used for space heating [Forintek, 1993]. Approximately 50% of the heat is derived from hogfuel.

Both van Heijningen (1992) and Forintek (1993) estimate the energy consumption of the production process at approximately 0.2 - 0.3 GJ_{el} and 6.8 – 7.2 GJ steam. We'll use the Forintek figures as estimates for the European situation in 2000.

For the production of plywood, phenol formaldehyde is widely used as adhesive [Forintek, 1993].The embodied energy is estimated 87 MJ/kg, 60% of which is feedstock energy. About 18 kg glue is used per ton of plywood, representing an energy input of 1.6 GJ/ton [Forintek 1993].

Cost of plywood production

We will estimate the production costs for plywood using the same method as for sawnwood and plywood production. The export price of plywood in Europe in 1995 is 755 ECU per m^3. Assuming 110 ECU per m^3 veneer logs and an input of 1.7 m^3 leads to a financial material input of 183 ECU per m^3 output. The cost of production therefore amount to 605 ECU per m^3 .

We will take the same figures for labor and O&M costs into account as for particle board production. Furthermore we assume an economic lifetime of the plant of 10 years, an interest rate of 10 % leading to an annuity factor of 0.15.

Table 3.4, Technology characteristics of the production of plywood

	2000	2020	2050
Input Resources (ton/ton)			
hardwood/softwood	1.4	1.4	1.4
glue	0.02	0.02	0.02
Output (tonne)			
Plywood	1	1	1
wood waste	0.4	0.4	0.4
Energy consumption (GJ/ton)			
Steam	6.9	6.9	6.9
Electricity (GJe/ton)	0.3	0.3	0.3
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	3333	3333	3333
O&M	133	133	133
o.w labor	106	106	106
transportation (km)	70	70	70
references	Forintek, 1993	van Heijningen, 1992	

3.4 The production of OSB

The OSB producing industry

Oriented Strand Board (OSB) is derived from waferboard, which was supposed to be *the* alternative for plywood (combining the high wood efficiency of particle wood with the good strength characteristics of plywood). Waferboard didn't live up to the expectations. The Americans took over the process and OSB became a popular board in the U.S.A. In Europe OSB has been compared with particle board for a long time and therefore it didn't become popular for a long time. Lately, OSB is compared with plywood and the growth is setting in. The largest production facility is located in Scotland with almost 75% of the European production capacity [Centrum Hout, 1996]. The current production capacity in Europe is 276.000 m3. At the moment the production capacity is increasing because two mills are being built with a total capacity of 400.000 m3 per year. Furthermore there might be developmets going on of further increase of the production capacity to 930.000 m3. A total European consumption of 1 million m3 in the future is expected [Centrum Hout, 1996].

OSB consists for 97% of wood (softwood) and 3% is glue and paraffine. The most common types of adhesives are phenol-formaldehyde, isocyanate, and melamine-ureaphenol-formaldehyde. OSB consists of three layers. Every layer consists of wood strands that are oriented in a certain direction. The layers are built up in such a way that the direction of the strands of the adjacent layers are perpendicular.

OSB is widely used for wood framed houses as a cladding material in the United States. The growth of OSB consumption in Europe is expected to be related to the growth of wood framed houses in Europe. Furthermore OSB can be used for roofs, floors, temporary buildings, fencing of building grounds, etc.

Energy consumption in OSB production industry

For the production of one ton OSB, 1.45 ton ‘oven dry’ roundwood is needed. The process also results in 0.45 tons of hogfuel/wood waste. Since OSB is not a very common wood based panel in Europe at the moment, no European studies have taken OSB into account when studying energy consumption in the wood industry. Forintek (1993) however, is a Canadian institute and it reports the following energy consumption figures: 0.84 GJ electricity per ton OSB is needed in the production process and 6.03 GJ of heat. About 80% of the heat that is required is generated by the hogfuel. We will use these figures as an estimate for the European situation in 2000.

Costs of OSB production

No international export prices of OSB are presented by FAO or UN-ECE. The reason for this is that many new wood based materials are developed lately and therefore it becomes very hard to define meaningful categories of wood based panels [UN-ECE, 1996]. We will use the cost figures of particleboard production as an estimate for OSB production.

Table 3.5, Technology characterization of the production of OSB

	2000	2020	2050
Input Resources			
softwood	1.45	1.45	1.45
glue	0.02	0.02	0.02
Output (tonne)			
OSB	1	1	1
wood waste	0.47	0.47	0.47
Energy consumption (GJ/ton)			
Steam	6.03	6.03	6.03
Electricity (GJe/ton)	0.84	0.84	0.84
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	1389	1389	1389
O&M	50	50	50
o.w labor	40	40	40
Transportation distance	1000	1000	1000
references	Forintek, 1993	FAO, 1997	

3.5 The production of Glulam

Glulam stands for Glued Laminated Timber, an engineered wood product. Glulams are composed of individual pieces of dimension lumber. The pieces are first end-jointed together to produce long lengths which are then bonded together with adhesives to create the required beam dimensions [APA, 1995]. Because pieces of wood are used for the production of glulams, large beams can be constructed from smaller trees (harvested from second and third growth forests and plantations).

Glulams have a greater strength and stiffness than comparable dimensional lumber. Therefore, the material is especially suited for long spanning long distances with minimal need for supports.

99% of the wood used for the production of glulam is spruce [Früwald, 1997]. The average moisture content of the wood input is 40%. The individual wood laminates are dried to a moisture content of 16% before they are being glued. After gluing the glulam beam is dried some more to an average moisture content of 12% [APA 1995].

The typical glue that is used in the production of glulam is a phenol-resorcinol-formaldehyde (PRF). Only 10% of the total energy use for the production of glulam is associated with the glue manufacturing, 90% is used is the production stage of glulam.

Energy consumption in the Glulam industry

Frühwald (1997a) states the energy demand in the production process of glulam at 6.7 GJ steam and 3.8 GJ_{el} per ton glulam. The steam demand corresponds well with Eichhammer et al. (1997) who estimate the steam demand at 6.72 GJ per ton. The electricity consumption however is over-estimated in Frühwald when compared to Eichhammer et al. (1997) who estimate it at 0.92 GJ_{el} per ton. As input for the MARKAL model we will use the average of these numbers.

In Germany 98.7% of the steam requirement is generated by using wood as fuel [Frühwald, 1997a].

Costs of glulam production

No prices for Glulam are available in international statistics. Because glulam is a much more value added product than sawnwood and comparable to plywood in that respect we will assume that the plywood production costs correspond to the glulam production costs.

Table 3.6, Technology characterization of the production of glulam

	2000	2020	2050
Input Resources			
sawn softwood	1.20	1.20	1.20
glue	0.04	0.04	0.04
other	0.01	0.01	0.01
Output (tonne)			
Glulam	1.00	1.00	1.00
wood waste	0.25	0.25	0.25
Energy consumption (GJ/ton)			
Steam	6.4	6.0	6.0
Electricity (GJe/ton)	2.2	3.4	3.4
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	5958	5958	5958
O&M	233	233	233
o.w labor	186	186	186
transportation distance (km)	70	70	70
references	Frühwald, 1997	Eichhammer et al., 1997	

3.6 Improvement options for the production of wood products

For the characterization of technologies for reducing the energy demand in the wood products industry it is important to have a good idea about the break down of the energy consumption in the processes.

The largest steam using step in the production process of all wood products is the drying stage. In table 3.7 an overview is provided of the share of the total steam demand that is necessary in the drying stage for several wood products.

Table 3.7: Share of total steam demand in the drying process of several wood products (in %) [Eichhammer et al., 1997]

	share of steam demand in drying stage
sawn wood	100
glulam	60
veneer	52
particle board	40

For the production of glulam the share of the steam demand in drying is estimated based on Eichhammer (1997) who categorized 25% of the steam demand as drying but another 55% was used for heating and conditioning of the raw material. For the production of OSB we will also assume a share of 40%

As mentioned in section 3.1 the steam demand in the drying stage can vary tremendously based on several factors. Variations of a factor 15 are not uncommon [Eichhammer, 1997].

Several methods exist for drying of wood. The most important ones are [Eichhammer, 1997]:

- Outdoor drying
- Fresh air drying
- Condensation drying
- Vacuum drying
- High temperature drying
- High frequency drying

Outdoor drying consumes very little energy but the drying times are very long (up to four years) and the quality of the wood deteriorates in some cases. This option will not be modeled for the MARKAL model because it is not very likely that this option will be chosen by industries in order to decrease the energy demand of a sawmill.

Fresh air drying is one of the most widespread used techniques and we will model this technique as standard option in the wood production processes. The air is circulated through the drying chamber by means of ventilators. The air temperature is generally around 65 °C but higher temperatures up to 90 °C are not uncommon. The energy demand of this technique is rather poor because the fresh air and exit air are continuously exchanged.

Condensation drying does not differ too much from fresh air drying except that the air system is closed. This leads to higher energy efficiencies. The primary energy use does not differ too much because the system works entirely on electricity (a electrical heat pulp is used for heating and evaporating).

Vacuum drying, high temperature drying, high frequency drying and infra red drying are nor modeled because disadvantages like very high energy consumption, quality problems or limited application [Eichhammer, 1997].

The energy consumption of fresh air drying and condensation drying are stated in Table 3.8.

Table 3.8: Energy consumption of two drying processes per m^3 dried wood [Eichhammer, 1997, Caddett, 1994].

	Electric (MJel.)	Thermal (MJtherm)
Fresh air drying	340	1026
Condensation drying	400 - 612	-

The data presented in Eichhammer (1997) are based on a report out of 1988. This may explain the small improvement of condensation drying compared to fresh air drying. Caddet (1994) shows that both the use of electrical heat pumps and avoiding remixing of exhaust and inlet (both are characteristics for condensation drying) lead to savings in primary energy of 30 - 33%. We will therefore use a electricity consumption of 400 MJel. per m^3 for condensation drying. Installation costs of condensation drying is assumed to be possible at no extra costs compared to fresh air drying because installation will occur when full depreciation of current drying technology has taken place.

The energy consumption of fresh air drying and condensing drying can be improved by installation of variable speed drives. This saves energy because the drying of wood consists of four stages: heating, drying, conditioning and cooling. During the drying stage, the velocity of the vans that circulate the heat can be reduced with 50% which leads to a reduction of energy of 85% in that period [Caddet, 1993]. A demonstration project at a Norwegian sawmill led to a total of 40% reduction on the fresh air drying stage [Caddet, 1992]. The cost of this project amounted to 54000 ECU or 39 ECU per GJ electricity saved. This equals 5.6 ECU per m^3 wood that is dried.

Combining the above leads to energy saving and cost data as stated in Table 3.9.

Table 3.9: Technology characterization of installation of variable speed drives in the wood processing industry

end product	savings (GJ_{el}/tonne)	costs (ECU/tonne cap.)
sawn softwood	0.28	115
sawn hardwood	0.22	85
wood based panel	0.22	85

4 Production of wood pulp for paper production

Pulping processes

Pulping is the process by which the fibers in the wood are separated and treated to produce a pulp. Pulp can either be converted into paper in an integrated pulp and paper mill or dried and transported to a paper mill. In Europe most paper mills are *not* integrated. Depending on the raw material and the desired product quality different pulping processes are used. The main categories are chemical, mechanical (high yield), semi-chemical, and chemi-mechanical.

In the U.S. the predominant process is chemical pulping. Based on the type of chemicals used different processes can be distinguished. The most common process is kraft (also called sulfate) pulping. About 80% of the pulp produced in the U.S. is kraft pulp. In the kraft process lignin is dissolved in a digester where the wood chips are cooked. Depending if the produced pulp is bleached or not, the average yield of the kraft process is 40-50% and 50-65% respectively. The lignin and other residues are used to produce electricity and heat.

In mechanical pulping the average yield is about 90% because the lignin is not extracted from the wood chips. Wood is pressed against a rotating grindstone or disks, which separates the fibers. Due to the damage done to the fibers in the process mechanical pulp makes a relatively weak paper. Furthermore the paper yellows relatively rapidly due to the presence of lignin.

Semi-chemical and chemi-mechanical pulping is a combination of chemical and mechanical treatment. Typical yields are 65%-85% and 85%-95% respectively.

Different types of pulp are used for the production of different paper grades. Mechanical pulp is used to produce newsprint and other printing and writing papers. Sometimes chemical pulps are added to improve strength and other qualities. Bleached kraft is mainly used in quality printing and writing papers. Unbleached kraft is used to produce linerboard and sack-paper. Semi-chemical and chemi-mechanical pulps are typically used to produce boxboard and sanitary products.

Lately, there are some shifts visible within the pulp production processes. Because of environmental concerns about current pulping technologies, new pulping processes are being developed. The most important techniques are solvent based pulping processes and the use of enzymes in pulping processes.

In the paragraphs 4.1 till 4.4 both the conventional and the new pulping processes are described in more detail.

Resources for pulp production

Wood is the most important feedstock for the production of paper. Due to concerns about the available forest resources, waste paper has become an important resource for the production of paper. The use of waste paper for paper production will be described in paragraph 4.5.

Besides the use of waste paper other sources can be used for paper production. Several initiatives have taken place to produce paper from non-wood resources because the use of wood as the main source of fiber for paper production has a few disadvantages. Firstly, the price of pulp made out of wood vary tremendously over the years and secondly, there is a growing concern about the world's wood resources.

The developments to produce paper from non-wood resources are not new at all because till the 1920's straw was the most important raw material for the production of paper.

The following crops are regarded as potentially useful nonwood fiber sources: cereal, rapeseed and linseed straw, miscanthus, flax, hemp and kenaf [Meeusen-van Onna 1996]. In table 4.1 the mean annual European production and average market price of these crops are stated. Straw based paper produced in Europe is currently confined to Spain, Denmark, Bulgaria, Rumania, Hungary and Turkey.

Table 4.1 Mean annual production and average market price in the EU (12 states) in the period 1990-1995 [Meeusen-van Onna, 1996]

	production (*1000 ODMT)	Market price (ECU/ODMT)
cereal straw	92650	47
Rapeseed straw	8500	47
Linseed straw	255	82
Miscanthus	0	55-100
flax short bast fiber	21-25	175-235
hemp whole stalk	38	70
hemp bast fiber	13	320
kenaf whole stalk	0	53-106
kanaf bast fiber	0	235-470

In Meeusen-van Onna (1996) it becomes clear that based on availability and costs wheat straw, hemp whole stalk, kenaf whole stalk and linseed are the most interesting fiber sources for paper production. In paragraph 4.6 we discuss differences in pulping processes for different fibers and the consequences for energy demand and costs.

4.1 Kraft pulping

The first pulping process that is described is chemical pulping or the Kraft-process. It is the most important pulping process in Europe with a total production of 19.6 million tons in 1995 [PPI, 1997]. This is an increase of more than 2 million tons compared to 1990 [PPI, 1997]. Most of the kraft pulp is produced in Scandinavia (13.6 million tons in 1995), where Finland and Sweden control almost 95% of the Scandinavian market. The European consumption (24.6 million tons) is higher than the production and therefore a net import of chemical pulp takes place [PPI, 1997].

The Kraft process uses a mixture of sodium hydroxide and sodium sulfide to pulp the wood (sulfate pulping). An alternative chemical pulp process is sulfite pulping which uses hydrogen sulfite or sulfite . The first process is the dominant production process in Europe (17.4 versus 2.2 million tons) [PPI, 1997]. In both processes the wood chips are impregnated with the pulping liquor and heated (under pressure) for a few hours.

After the digester, the fibers are separated from the liquor by counter-current washing. The pulp is then screened, often bleached, and pumped to the paper mill or dried before shipping it from the mill.

The bleaching process requires a lot of chemicals like chlorine, chlorine dioxide, oxygen, hypo-chloride, hydrogen peroxide and ozone. Modern mills use oxygen delignification to reduce the amount of lignin after the digestion stage and before the bleaching section. In this way reducing the amount of bleaching chemicals needed.

By using chlorine dioxide instead of chlorine, ECF paper is produced (elemental chlorine free). The demand for totally chlorine free (TCF) paper lead to the introduction of hydrogen peroxide and ozone as bleaching agents.

The spent pulping liquor is evaporated to increase the solids content and then goes to the recovery section where it is burned in a Tomlinson recovery boiler. Steam and electricity are generated by Condensing Extraction Steam Turbine (CEST). The inorganic chemicals are recovered as a smelt of sodium sulfide and sodium carbonate. White liquor is regenerated by adding calcium hydroxide to the solution of the melt and water. Calcium carbonate is burned in a lime kiln to produce calcium oxide which reacts with water to form calcium hydroxide. The burning of calcium carbonate leads to a emission of CO_2. However, the carbon in $CaCO_3$ originates from lignin that is dissolved in the process. This carbon emission is already taken into account when the energy production by recovery of black liquor is calculated.

Energy efficiency measures in a kraft pulp mill.

Major steam users in a kraft pulp mill are the digesters, evaporators, and the pulp drier. These processes account for about 75% of the steam use of the pulp mill.

The electricity use is more evenly distributed over the mill. Pumps and fans are the major consumers, 40-45% and 15-20% respectively.

Energy consumption reduction is/can be achieved by:

- *modified cooking or extended delignification*. The basic principle of modified cooking is more selective delignification by controlling the alkali concentration during the cook. By charging the alkali in three stages the concentration remains more constant during the cook. Oxygen delignification reduces the lignin content after cooking. Heat and electricity demand increase by 0.5 GJ/ADMT and 75 kWh/ADMT respectively which is compensated by a higher recovery of organics. Economic savings come from lower chemical consumption. Energy can be saved by using the high grade heat in the spent pulping liquor to preheat white liquor and chips. 30-78% can be saved[Nilsson, 1995].

- *medium consistency processing.* Large amounts of electricity is used by pumps. Due to the low consistency of the pulp, 1-3% in washers, 1% in screening and 3-12% in bleaching large amounts of water have to be pumped. Increasing the overall consistency of the pulp (8-15%) can lead to 10% reduction of the energy consumption[Nilsson, 1995].

- *bleaching.* Fewer bleaching steps will decrease electricity use. Most chemicals are purchased and therefore the energy use for producing these chemicals are not taken into account. Due to the increasing demand for TCF paper, ozone is used for bleaching which is produced on site. This leads to a 5-10% increase in on-site electricity demand. Furthermore investment costs will increase by 10%. Rapid development of TCF bleaching technology could reduce these differences[Nilsson, 1995].

-*Pulp drying.* Most of the energy used in the dryer is used to evaporate the water. By using state of the art double wire technology, the consistency of the pulp before drying can reach 50% (instead of 45% normally) [Nilsson, 1995].

-*Black liquor evaporation.* Black liquor concentration is usually the biggest steam using operation in a kraft pulp mill. Black liquor is evaporated by heating it with steam (140°C). Water evaporates which is used in the next drying section (multiple effect evaporator, MEE). By using more effects, less steam is required for this operation. Modern mills use a 5-6 effect evaporator while older mills use 4-5 effects. To minimize steam use 6-7 effects are used. Large steam savings can be achieved by using less water in the brownstock washing (where the fibers are separated from the spent pulp liquor) [Nilsson, 1995].

-*Black liquor gasification*. The black liquor is gasified and the flue gasses are used to fuel a gas turbine/steam turbine combined cycle. This improvement option will lead to pulp mills that are net exporters of electricity.

Energy data for Kraft pulping

In Table 4.2 we assume that an average European kraft mill in 1990 corresponds with the average of the 1980 model mill and the 2000 model mill as described in Nilsson (1995)[3]. For 2000 we assumed the 2000 model mill to be representative for the European situation in 2000. The model 2000 mill is a kraft pulping mill extended with modified cooking, oxygen delignification and elemental chlorine free bleaching. Furthermore, medium consistency processing is used. The energy efficiency of the model 2000 mill is almost equal to a new 1990 Swedish bleached kraft pulp mill as described in Larson (1992).

Most of the energy use in a Kraft mill is generated by using the black liquor as fuel. Furthermore bark is used as fuel. Approximately 70% (in 1990) of the energy demand is satisfied with wood residues. We modeled the recovery unit separately from the rest of the Kraft mill (Tables 4.3 and 4.4). The reason for this is that the black liquor might also be used for other purposes than energy recovery. In Table 4.3 we model the traditional Tomlinson recovery boiler. In table 4.4 we assume that till 2020 the black liquor is recovered in a Tomlinson recovery boiler and that the produced steams is used in a CEST-unit. For 2020 we assume that gasification of black liquor is a common technology. The fuel gas is burned in a Biomass Gas Turbine. The whole system is referred to as Biomass Integrated Gasifier/ Gas Turbine (BIG/GT) [Larson, 1991]. By using the gasification technology Kraft mills will produce an excess of electricity and generate enough steam to meet their own steam consumption.

Investment data and other costs of Kraft pulping mill

Kraft pulping is a very capital intensive process. The investment costs are estimated by Komppa (1993) at $800 million for a typical 450.000 tons/yr mill. In PPI (1996) and PPI (1997) the expansion activities of the largest pulp and paper companies are described. They report on 4 kraft mills that are ordered in the last few years. The investments vary strongly. The reason for this is probably related to the location and the quality of the output produced.

Figure 4.1 shows the investment costs and the mill size of these ordered kraft mills. This figure shows clearly that the investment costs are related to other factors than the mill size.

Mill 1 is the mill described by Komppa, Mill 2 and 3 are entire mills that are ordered by Champion and UPM respectively and Mill 4 and 5 are expansion investments in existing mills (extra pulping lines). Based on these data we will use the average investment costs of $1500 per ton.

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[3] In Nilsson (1995) two hypothetical kraft mills are modeled for 1980 and 2000. It represents what is possible using 1980-vintage and 2000-vintage technology in a greenfield mill.

The other manufacturing costs are based on Ince (1994), where manufacturing costs are estimated for the NAPAP model. Furthermore Ince (1994) estimated the amount of labor for the production of a ton kraft pulp at 0.25 hours.

Several studies have been done for the potential of black liquor gasification. The costs seem comparable with the traditional recovery boiler. In Larson (1992) the cost of a black liquor gasification unit is estimated at $70 million for a pulping capacity of 350.000 ton/year. This is the same as for a recovery boiler [Larsson, 1992]. In McKeough et al. (1996?) a gasification plant is compared to a tomlinson recovery boiler and they estimate the black liquor system at $130 million and a tomlinson recovery boiler at $100 million for a mill with a capacity of 2000 tons pulp per day.

This results in investments of $202 per ton capacity for the gasification plant and $145 per ton for the Tomlinson boiler. In these figures the costs for the steam turbine, gas turbine, feed water system etc. are included.

Figure 4.1, Investment costs and mill size of several Kraft pulping mills [PPI, 1996 and PPI, 1997]

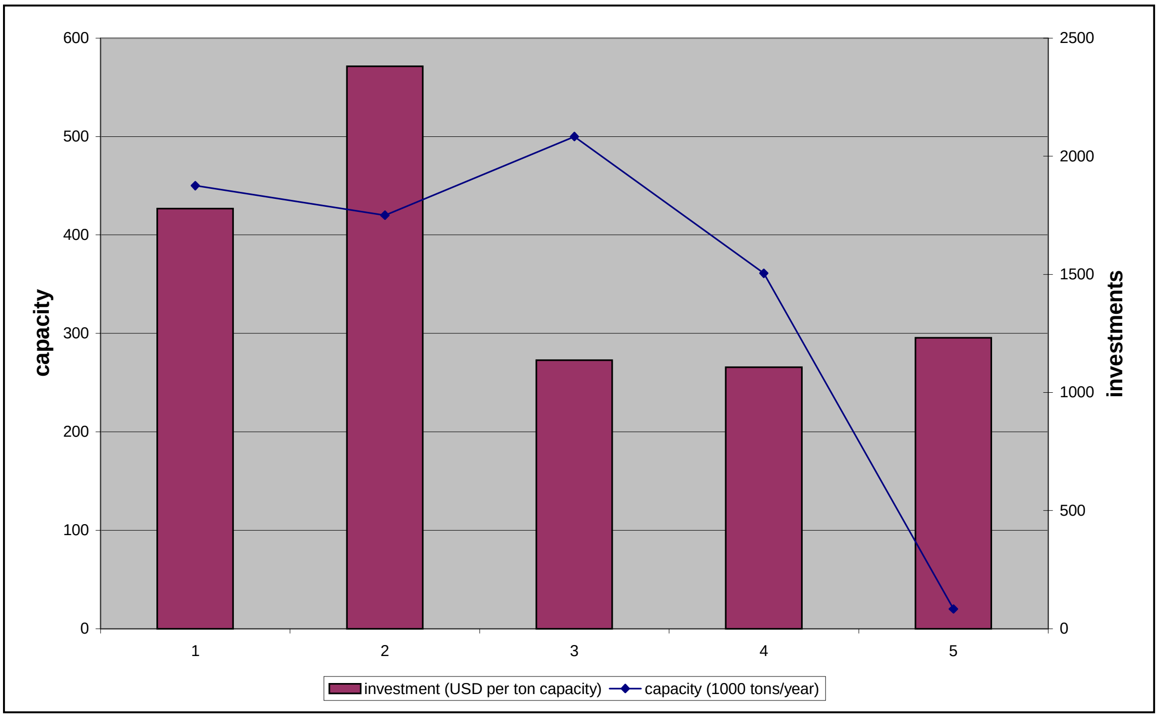

Table 4.2, Technology characterization of the production of Kraft pulp for the Matter Project.

	2000	2020	2050
Input Resources (tonne)			
wood	2	2	2
Output (tonne)			
Kraft pulp	1	1	1
Black liquor (GJ)	23	23	23
Bark (GJ)	4	4	4
Energy consumption (GJ/tonne)			
Steam	7.8	7.8	7.8
Electricity (GJe/ton)	2.3	2.3	2.3
Costs (ECU/tonne)			
Investments	1355	1355	1355
O&M	75	75	75
o.w. labor	60	60	60
References	Ince, 1994 Komppa, 1993	PPI, 1996 Nilsson, 1995 PPI, 1997	

Table 4.3, Technology characterization of the recovery of black liquor with a Tomlinson recovery boiler

	2000	2020	2050
Input Resources (GJ/tonne pulp)			
black liquor	23	23	23
Bark	4	4	4
Output (GJ/tonne pulp)			
Steam	14.4	14.4	14.4
Electricity	2.16	2.16	2.16
Costs (ECU/tonne)			
Investments	145	145	145
O&M	7	7	7
References	Nilsson, 1995 Larson, 1991	PPI, 1997 McKeough, 1996	PPI, 1996

Table 4.4, Technology characterization of the recovery of black liquor using a gasifier + BIG/GT combination boiler

	2000	2020	2050
Input Resources (GJ/tonne pulp)			
black liquor	23	23	23
Bark	4	4	4
Output (GJ/tonne pulp)			
Steam	11	11	11
Electricity (GJe/ton)	6.5	6.5	6.5
Costs (ECU/tonne pulp)			
Investments	202	202	202
O&M	11	11	11
references	Nilsson, 1995 Larson, 1991	PPI, 1997 McKeough, 1996	PPI, 1996

4.2 Mechanical pulping

Mechanical pulping is a common technology in Europe. About 11.1 million tons was produced in 1995 at a total of 32 million tons [PPI, 1997]. This is a large share compared to the situation in the United States where only 5.5 million tons are produced at a total of

60 million tons [PPI, 1997]. Just like chemical pulp production, most production capacity is located in Scandinavia (about two thirds) [PPI 1997].

Mechanical pulping is a pretty straight forward process by which the wood chips are grained against rotating disks to separate the fibers. Because the lignin is nor dissolved by chemicals like in chemical pulping, the process has a very high yield. Typical yields are in the order of 90%.

High yield pulping processes are electricity intensive. The demand varies considerably depending on the quality of pulp produced.

Most improvement in energy efficiency has resulted from improved heat recovery where the recovered steam is used to dry the paper in an integrated mill.

For a single pulp mill possible electricity savings are reported of 30% [Christiansson, 1995] by changing the operating strategy. Improvement options are: improving process control, higher refiner speed, double disc refiners instead of single disc, refining at lower concentrations and various forms of pretreatment.

Energy and cost data for mechanical pulping

In Table 4.5 data from Nilsson (1995) and Komppa (1993) are used. Nilsson (1995) describes a typical Swedish mill from 1988 and gives some projections for future mill performances. Komppa (1993) states data for a modern Finnish TMP mill. Nilsson (1995) estimates a lower energy consumption for TMP mills than Komppa (1993). We expect that Scandinavian pulp mills are more efficient than the European average. We therefore took the modern mill values from Komppa (1993) for the European average for 1990. For 2000 we took the lower value for modern TMP production from Nilsson (1995). We assumed that the Swedish estimates for 2005 would be relevant for Europe in 2010 [Nilsson, 1995].

The investments costs of a mechanical pulp mill are very much lower than for a chemical pulp mill. Komppa uses figures of $25-35 million but doesn’t state any capacity figures. In PPI (1996) only one order of a TMP mill is mentioned. It involves a mill with a capacity of 600 tons/day (about 20,000 tons/year) and investment costs of $60 million. This results in $300 per ton of capacity. We will use this number as an estimate for the capital costs of a TMP plant.

Table 4.5: Technology characterization of the production of TMP

	2000	2020	2050
Input Resources (ton/ton)			
wood	1.1	1.1	1.1
Output (tonne)			
TMP pulp	1	1	1
Energy consumption (GJ/ton)			
Fuel			
Steam	-2.53	-3.5	-3.5
Electricity (GJe/ton)	7.92	5.3	5.3
Costs (ECU/ton)			
Investments	300	300	300
O&M	17	17	17
o.w. labor	13	13	13
references	Komppa, 1993	PPI, 1997 PPI, 1996	

4.3 Solvent-based pulping processes

Solvent-based pulping processes are invented to replace the Kraft-process some day. The reason for this is that the Kraft-process has a few disadvantages that might be resolved by the solvent-based processes. The first disadvantage is from an environmental point of view and it involves the concerns about the sulfur, dioxin and absorbable organic halides (AOX) emissions. The second disadvantage is associated with the enormous costs associated with building a kraft mill. The economics favor large systems e.g. 1000 tons per day which leads to problems about the location of the mills because a mill can only operate with a large supply of wood [Stockburger, 1993].

Solvent-based pulping processes (also called organosolv processes) might overcome the disadvantages of the Kraft process by using organic solvents as methanol and ethanol instead of sulfur based chemicals for the pulping process. Besides lower emissions the costs of the processes are also likely to be lower because the processes don't need a large and complex recovery system as the Kraft process.

Promising processes that are being developed are Organocell and Alcell. Another process that is also considered as a solvent-based pulping process is the ASAM (alkali-sulfite-anthraquinone-methanol) process. However, just like the Kraft-process it uses sulfite for the actual delignification of wood. Therefore the disadvantages of the Kraft-process are also the case for the ASAM process e.g. high recovery costs of chemicals. The process is more environmentally friendly because it does not produce reduced sulfur compounds and lends itself very well for chlorine free bleaching. The major advantages of this process are seen in the higher yield and lower lignin residual content of the pulp.

We will not get into this process in more detail, neither will we model is technology as an improvement option for the Kraft process because the costs are considered to be even higher than for the Kraft process and the improvement in energy efficiency is not clear [Stockburger, 1993].

The Organocell process is a typical solvent-based process that uses sodium hydroxide, methanol, and catalytic amounts of anthraquinone for the delignification process. The process is invented by Organocell GmbH and a demonstration plant of 5 tons a day is running since 1987. Since then the process is improved from a two step process to a single step process. The process involved cooking of wood chips in a mixture of water and methanol (30%) with addition of sodium hydroxide (20%) and anthraquinone. After cooking the methanol is recovered by distillation and sodium hydroxide is recovered by the conventional kraft recovery process [Stockburger, 1993].

The Organocell process results in a good quality pulp which can be bleached more easily than kraft pulp. A disadvantage is that is uses sodium hydroxide so a recovery unit is still necessary which leads to large scale mills.

In 1992 Organocell started up a 150.000 ton/yr. mill in Germany. It proved to have very low emissions to air and water [Weidenmuller, 1992]. The investment costs of the mill were about DM 750 million [anon. 1992]. The mill produces lignin that is not polluted with sulfur compounds. The lignin was used for energy production but it was supposed to be used later for the production of high-quality products like wood adhesives and insulation products [anon. 1992, Stockburger, 1993]. In 1993 Organocell was declared bankrupt and the project stopped [Anon. 1995]. Still it the Organocell process is likely to become a viable option in the future for the production of pulp [Stockburger, 1993]. The process is also tested on laboratory scale on hemp pulping and it showed to be a possible successful option [Zomers et al., 1995].

The last solvent-based pulping process that is descrobed here is the Alcell process. It is a pulping process that is employs a mixture of water and ethanol as the cooking medium. Since 1989 this process is tested with a 15-ton/day pulping unit in Canada. The process can be described as follows: The wood chips are cooked in a 50:50 mixture of ethanol and water to extract the lignin, the lignin and the liquar are recovered and the other byproducts are recovered. Three byproducts are generated: lignin, furfural (can be used for lubricating oil production) and wood sugars. At Alcell work is been done to convert the wood sugars into furfural.

The method is significantly cheaper than the Kraft process because no recovery unit is necessary in the process. Also the Alcell process can be exploited with smaller mills. The byproducts have to be sold on the market and therefore the process needs to purchase power from the grid. The economics of Alcell depend therefore on the market value of the byproducts. The main disadvantage at this moment is that the Alcell process is only applicable to hardwoods. Therefore the market is very limited at the moment [Stockburger, 1993].

At the moment no information is available on the energy efficiency of the pulping process. However when the purposes of inventing this process are taken into account it is not very likely that the energy requirement will be much lower than for the traditional kraft process. Also the production costs of the Organocell process are likely to be the same as for Kraft pulping. We will therefore not model this option for MARKAL.

4.4 Biopulping and other enzyme related processes in pulping

In the last decade microbial enzymes are starting to be used commercially in the pulp and paper industry. Enzymes can be used for many different purposes. The following areas are very promising.

1. Improvement of drainage rate of a pulp. The drainage rate is the amount of water loss during paper formation and it determines the speed of the paper machine. This is especially important for recycled fibers because they tend to have smaller drainage rated than virgin fibers [Kirk and Jeffries, 1996]. This process is commercial in France [Kirk, 1994].

2. Modification of pulp properties. Enzymes can improve several pulp properties like reduction of picking (incomplete contact of paper with ink due to large vessels) by reduction of vessel length and a second improvement in the increase in fiber strength [Kirk and Jeffries, 1996].

3. Pitch removal. A pitch is a hydrophobic component of wood resin, tryglyceride or waxes that negatively influences water absorption by the pulps, tearing of the paper during drying and discoloration. These problems during paper making can be reduced by using enzymes that are capable of lowering the triglyceride content of the pulp and therefore lowering the amount of pitches [Broda, 1995, Kirk and Jeffries, 1996].

4. Bleaching. Enzymes can be used very effectively in the bleaching process of kraft pulp. Kraft pulp is often bleached because large quantities of chromophores are present at the end of the pulping process. Chromophores are composed of residual lignin and carbohydrate degradation products. Normally chemicals are used to bleach and extract the chromophores (see paragraph 4.1). Nowadays enzymes are used commercially as aids in pulp bleaching. Fungal xylanases is used for the enzymatic pre-bleaching so less chemicals are needed in the final bleaching process. This process is the biggest success story in the use of enzymes so far due to regulatory pressure against chlorine and savings of chemical costs. Sales of Xylanases are already $20 million per year in the U.S. and are projected to be $200 million [Broda, 1995].

5. Biopulping. Biopulping is defined as the treatment of wood chips with lignin degrading fungi prior to pulping [Scott et al. 1997]. Biopulping is used in the mechanical pulping process. Besides al kind of advantages for paper properties and process improvements it reduces the amount of electrical energy needed in the pulping process [Scot et al. 1997, Kirk, 1994].

The points listed above suggest that it will not take a very long time before enzymes will be a common good in the pulp and paper industry. From an energy point of view biopulping is the most promising application.

Biopulping

As stated before biopulping is an energy saving technology for the *mechanical* pulping process. In Figure 4.2 a schematic representation of the biopulping process is stated.

Figure 4.2: Overview of the biopulping process (based on Scott et al., 1997).

Figure 4.2 shows that biopulping fits into an existing mechanical pulp mill because only small adaptations are made to the existing wood-handling system. The wood is harvested and transported to the mill site for debarking, chipping and screening. Than the chips are decontaminated by steaming and cooled afterwards. These steps that differ from the normal wood handling system are necessary to allow the fungus to grow effectively. After cooling the fungus is applied and the retention time in the pile is 1 to 4 weeks [Scott et al., 1997]. This is considerably shorter than normal because than the wood is seasoned for three months [anon, 1991].

The inoculum is added as a mixture of fungus, corn steep liquor and water. The corn steep liquor is added because less fungus is needed for the same result. In Akhtar et al. (1994) it is stated that the amount of inoculum can be lowered from 0.3% (dry weight basis) to 0.0005% or less by adding corn steep liquor. This is an interesting option because in contrast with the inoculum corn steep liquor is inexpensive.

To determine the amount of energy that can be saved by using the lignin degrading fungi many tests on laboratory scale have been done. One of the leading organizations in this field is the USDA Forest Products Laboratory. They report energy savings of 46% to 51% when biomechanical pulp is compared to refined mechanical pulp on a laboratory scale [Kirk et al., 1992]. In 1994 energy savings are reported between 14% and 42% based on the type of fungus used [Akthar et al., 1994]. The latest publication shows savings between 25% and 40% under scaled-up conditions [Scott et al., 1997]. The process is still not commercially available. As input data for the Markal model we estimate that only a small percentage of the mechanical pulps will be produced with biopulping technology with a reduction in the specific energy consumption of 25%. The next sight year is 2020. We expect that this process will be available for all mechanical pulping plants with a minimum improvement of the energy efficiency with 40%.

In Scott et al. (1997) also an economic analysis of the biopulping process is stated. It is expected that the process requires a capital investment of $6 million for a 600 ton/day mill. In Kirk et al. (1992) approximately the same figures are mentioned.

Table 4.7: Energy and cost data for the production of TMP, using enzymes.

	2000	2020	2050
Input Resources (tonne)			
wood		1.1	1.1
Output (tonne)			
TMP pulp		1	1
Energy consumption (GJ/ton)			
Steam		-2.1	-2.1
Electricity (GJe/ton)		3.2	3.2
Costs (ECU/tonne)			
Investments		330	330
O&M		18	18
o.w. labor		15	15
penetration (%)	0	100	100
references	Scott et al., 1997 Komppa, 1993	PPI, 1996 PPI, 1997	Akthar et al., 1994

4.5 Production of pulp from nonwood fibers

Nonwood fibers are used for a long time for the production of paper. The technology is more common in developing countries than in Western Europe but lately more attention is directed towards different resources.

Statistics do not separate pulp based on wood and pulp based on non wood resources. Therefore it is not possible to state figures concerning the current use of nonwood resources for pulp production in Europe at the moment.

In the US many research activities concerning the use of nonwood resources in pulp making are being conducted. The Forest Products Laboratory, for example, tested kenaf chemithermomechanical pulp for the production of printing and writing papers. The tests showed that Kenaf CTMP is marginally acceptable by itself in printing and writing grades [Myers and Bagby, 1995]. It is however a good reinforcing pulp for the production of recycled newsprint (up to 25%) and a pulp mix with up to 50% kenaf can produce an acceptable linerboard.

The reason for testing kenaf as an alternative fiber source in U.S. paper making is that the yield per acre (6 tons/year/acre) is twice the yield of sourthern pine, a regular used fiber source in the United States. Furthermore the production costs vary between 100-120 dollar per ton while southern pine is delivered at 120-180 dollar per ton [Sabharwal et al., 1994].

Kenaf was also tested as a fiber source for the production of mechanical pulp. These tests showed that producing a mechanical pulp from kenaf uses 1080 kWh per ton compared to 1861 kWh per ton for pulping of wood (42% savings). When kenaf is bio-treated before pulping the energy demand is only 780 kWh per ton [Sabharwal et al., 1994]. This means a saving of 30% compared to biotreated wood (1122 kWh/ton).

In Europe most experience with nonwood resource pulping is gained in Spain, Denmark and Eastern Europe. In Spain the leading producer of corrugated materials (Saica) uses straw to upgrade waste paper pulp in the production of linerboard and fluting. The straw pulp content in the pulp mixture varies between 20% and 50% and the most common used straws are rye, wheat and barley. Saica produces about 400 tons semi-chemical straw pulp per day [Marcus, 1994].

In Croon (1992) is becomes clear that miscanthus is a good fiber source for the production of coated printing and writing papers while straw has good qualities for the production of liner and packaging board.

Jute is also a very promising nonwood fiber for the production of paper products. It is mostly grown in Bangladesh, India, China and India but is well suited for paper production in developed countries. Tests that have been done by the U.S. Department of Forest Products have shown that mechanical pulping of jute is less energy intensive than mechanical pulping of wood and other nonwood fibrous materials. Furthermore, large energy savings can be obtained with biopulping of jute bast. Energy savings of 1150 kWh per ton of pulp are reported if wood pulp is replaced by bio-mechanical jute pulp [Sabharwal et al., 1995].

Modeling nonwood pulp production can focus on all basic pulping technologies. In principle nonwood pulp can be obtained by the Kraft process, semi-chemical or semi-mechanical pulping and mechanical pulping. Most energy efficiency improvements are reported for the mechanical pulping process. We will use this process for modeling nonwood pulp production. The energy efficiency improvements compared to normal mechanical pulping will be based on Sabharwal et al. (1994) and Sabharwal et al. (1995). These figures are specifically for kenaf and jute but we will presume that these figures are representative for all nonwood pulping processes.

In Table 4.8 mechanical pulping of nonwood resources is modeled and in Table 4.9 biopulping of nonwood resources is modeled. Both tables lean strongly on the TMP data concerning investment costs.

Table 4.8: Technology characterization of the production of mechanical pulp from nonwood resources.

	2000	2020	2050
Input Resources (tonne)			
nonwood resources		1.1	1.1
Output (tonne)			
Non wood pulp		1	1
Energy consumption (GJ/ton)			
Steam		-3.0	-2.0
Electricity (GJe/ton)		4.6	3.1
Costs (ECU/tonne)			
Investments		300	300
O&M		18	18
o.w. labor		14	14
penetration grade (%)	0	100	100
references	Sabharwal et al., 1994	PPI, 1996	PPI, 1997

Table 4.9: Technology characterization of for the production of nonwood pulp, using enzymes

	2000	2020	2050
Input Resources (tonne)			
non wood resources		1.1	1.1
Output (tonne)			
non wood pulp		1	1
Energy consumption (GJ/ton)			
Steam		-1.5	-1.5
Electricity (GJe/ton)		2.2	2.2
Costs (ECU/tonne)			
Investments		330	330
O&M		18	18
o.w. labor		14	14
penetration (%)	0	100	100
references	Scott et al., 1997	PPI, 1996	Akthar et al., 1994
	Komppa, 1993	PPI, 1997	Akthar et al., 1995

4.6 Pulping of waste paper

Waste paper is the second most used fiber source for the production of paper, next to virgin wood fibers. Waste paper recovery in Western Europe increased from 13185 ktons in 1975 to 30680 ktons in 1995 [PPI, 1997]. Also the import of waste paper into Europe increased from 2537 to 7210 kilotons in the same period [PPI, 1997]. For future years, still a large growth in waste paper recovery is expected. Jaakko Poyry Consulting expects an annual growth in waste paper recovery of 3.9 % resulting in a projected waste paper recovery of 39300 ktons in 2005 in Western Europe [IIED, 1995].

In principle all paper waste can be used for the production of paper. The quality of the paper waste however has a large influence on the quality of the paper produced. Mixed waste paper can only be used for the production of low grade paper and board. Waste papers that are properly separated have a higher value. Many different waste paper grading systems are used at the moment. In The United Kingdom for example 11 groups of waste paper are discerned and many more sub-categories are in use.

For the Markal model it is not necessary to discern so many types of waste paper. In Virtanen and Nilsson (1993), which describe a detailed model for analyzing the environmental impacts of waste paper recycling, four types of waste paper are discerned:

1. highly printed waste paper with a majority of newsprint

2. Slightly printed or unprinted waste paper

3. Composite paper and boards, e.g., liquid packages

4. Mixed waste paper, a mixture of (1), (2), and (3).

Furthermore, two techniques are used to produce pulp based on these waste paper types.

The Confederation of European Paper Industries discern also 4 different waste paper grades which correspond to the FAO classifications [CEPI, 1995]:

1. Old Newsprint: Old newspapers and magazines, brochures etc. (mainly mechanical pulp)

2. Corrugated: Corrugated, solid container and kraft sack waste (mostly unbleached)

3. Woodfree: Woodfree writing and printing paper, copy paper, computer print outs and other high grade qualities (mainly bleached)

4. Others: All other types.

For the Markal model we have a choice between modeling the waste paper qualities like Virtanen and Nilsson (1993) or like the CEPI/FAO definitions. We will use the latter because it corresponds better with the paper grades that we defined (also according to the FAO definitions).

We will use the same two ways of waste paper upgrading as defined in Virtanen and Nilsson (1993). The difference between the two types of upgrading plants is the quality of the waste paper output. For newspaper production and for the production of graphical paper high waste paper pulp qualities are necessary. A modern deinking mill should be modeled to produce these types of pulp. For the production of packaging paper and board a mill can be modeled that produces non-deinked waste paper pulp.

These two types of waste paper upgrading are also used in statistical sources. The CEPI statistics show that in the period 1991-1997 the total capacity for waste paper recovery increased from 23 million tons to 35 million tons. In the same period the capacity of deinking mills showed a stronger growth than the non-de-inking mill capacity. The deinking capacity doubled from 6 million tons to 12 million tons between 1991 and 1997 but the non-de-inking capacity is still about twice that size [CEPI, 1997]. This corresponds to the waste paper usage figures which show that the case materials industry uses 44.9% of all waste paper used (the newspaper industry comes on second place with 13.6%) [CEPI, 1995].

A simple waste paper plant and a de-inking plant differ considerably on certain processing steps. The major difference of course is the presence of a deinking facility.

Still, a waste paper plant consists normally of the following general steps [McKinney, 1995]:

- Pulping
- Coarse screening and cleaning
- Fine screening and cleaning
- Other processes
- Thickening and storage

During pulping the waste paper is defibered and contaminants are removed. The objective of the screening and cleaning phase is the removal of non-fibrous contaminants, with minimal losses of useful fiber.

For every stage many different types of equipment are available on the market and significant improvements have been made over the years to improve the processes. The pulping process for example has developed from low consistency pulping to high consistency pulping. This is done because high consistency pulping uses less energy because less water needs to be moved and contaminants are not degraded as much as in low consistency pulping so they can be removed more easily later on. The typical energy requirement of a low consistency pulper is in the range of 30-45 kWh per ton while a high consistency pulper uses 15-25 kWh per ton [McKinney, 1995]. Also developments are going on to replace batch pulpers with continuous pulpers.

Also in the deinking section large improvements have been made. Deinking can be done by two methods: washing and flotation. Till the 1970's they were seen as two competitive systems instead of complementary systems. Large difference in deinking technologies are used in different parts of the world. The European system usually first uses flotation and than a washing stage follows while the Japanese mills usually do it the other way around and thereby creating different pulp properties [Read, 1991].

Wash deinking is very well suited for removing the small ink particles and flotation is more efficient for removing the large particles (>20 micrometer).

The principle of washing is very simple: ink is broken up on pulping and some of these in particles are removed by subsequent wash stages with the washer filtrate. Flotation is based on a through put of air bubbles through the pulp solution. The ink particles collide with the air bubbles and rise to the surface where they can be separated as foam from the pulp solution by overflow, suction etc. Large improvement in increasing the energy efficiency of flotation has been established, from 84 kWh per ton to 40-65 kWh per ton [McKinney, 1995].

Energy use and costs of waste paper upgrading

Most about the energy use and costs of waste paper upgrading is known for deinking mills. In McKinney (1995) a complete deinking mill for the production of newsprint is described. The electricity input is 600 kWh per ton pulp (2.16 GJ_{el}) and also a steam input of 1 MJ is required.

In Virtanen and Nilsson (1993) an electricity consumption of 472 kWh (1.70 GJ_{el}) per ton pulp and a steam consumption of 1.12 MJ is assumed for 'brown waste paper pulp' (no deinking stage involved).

Byström and Lönnstedt (1995) are more optimistic concerning electricity input. In their waste paper recycling model they use 1.5 GJ_{el} for the deinking process, furthermore a heat input of 2 GJ is assumed.

McKinney (1995) states that the capital investments for a waste paper upgrading mill are the same as for a TMP pulping mill. Janda (1995) states that the investments of a modern deinking mill are $70 million for a capacity of 275 tons of pulp per day ($734 per ton capacity). In Cesar and McBride (1994) investments are reported of $27 million for a 100 tons per day capacity ($779 per ton capacity). Furthermore, from PPI (1997) can be learned that paper manufacturer AMCOR ordered a waste paper upgrading plant of about $36 million with a capacity of 65000 tons per year ($554 per ton capacity). In Figure 4.4 these investments costs are compared. The low investment data for the AMCOR mill might be due to the fact that the mill is built in Australia.

The yield of the process is calculated at 85% by McKinney (1995) for the newsprint quality pulp which corresponds to yield figures stated in Frenzel (1995). For higher paper grades lower yields are not uncommon. James River started up a new deinking plant in 1992 for the production of high quality pulp for the production of white office papers and sanitary papers. This mill has a yield of 69% [Janda, 1995].

A labor input of 0.36 hours per ton of pulp output are required for the production of waste paper pulp[McKinney, 1995].

As stated earlier, two paper upgrading mills will be modeled. One type for the production of high quality papers, using a deinking mill. The other is used for lower grade pulp production and no deinking facility will be part of that mill.

The energy consumption of the processes will differ. We will use the energy requirements as stated by McKinney (1995) for the production of high quality deinked pulp. For the lower quality pulp, no deinking is necessary and therefore less energy is needed. We will use the figures of Virtanen and Nilsson (1995) because they modeled the production of low quality 'brown' waste paper pulp.

The waste paper upgrading technology is still being improved. The energy figures stated in McKinney (1995) and Virtanen and Nilsson (1995) might be completely different in

2020. In Cesar and McBride (1994) optimistic energy data are presented. They also state energy efficiency improvements by the use of chemicals. Furthermore, The Forest products laboratory is doing research in improving the deinking process with enzymes. Already they are working on up-scaling deinking facilities that use enzymes [Heisse et al., 1996], . No figures are reported about energy efficiency improvements but it may be expected that significant savings can be the result of such research. For the year 2020 we will therefore use the energy figures stated in Cesar and McBride (1994) for the chemi-mechanical pulping (300 kWh/ton). The same improvement (in percentage points) is used for the other waste paper upgrading process.

The investment costs will also differ for the two processes. Data are available on three mills and all of these are contain deinking facilities. We will assume that the average investment costs are representative for the European situation for high quality pulp production. No data are available on waste paper facilities that do not use deinking facilities. We will use the AMCOR data as an indication of these investment costs in Europe.

Depending on the quality of pulp produced the yield of the process differs. For high quality graphical papers we will use an efficiency of 69%, for newsprint production we will use a yield of 85% (both deinked pulp). For the low quality pulp process for packaging paper and board we will use a yield of 89% based on Virtanen and Nilsson (1995).

Figure 4.4: Investment costs and capacity of waste paper upgrading plants [Janda, 1995, Cesar and Mcbride, 1995, PPI, 1996]

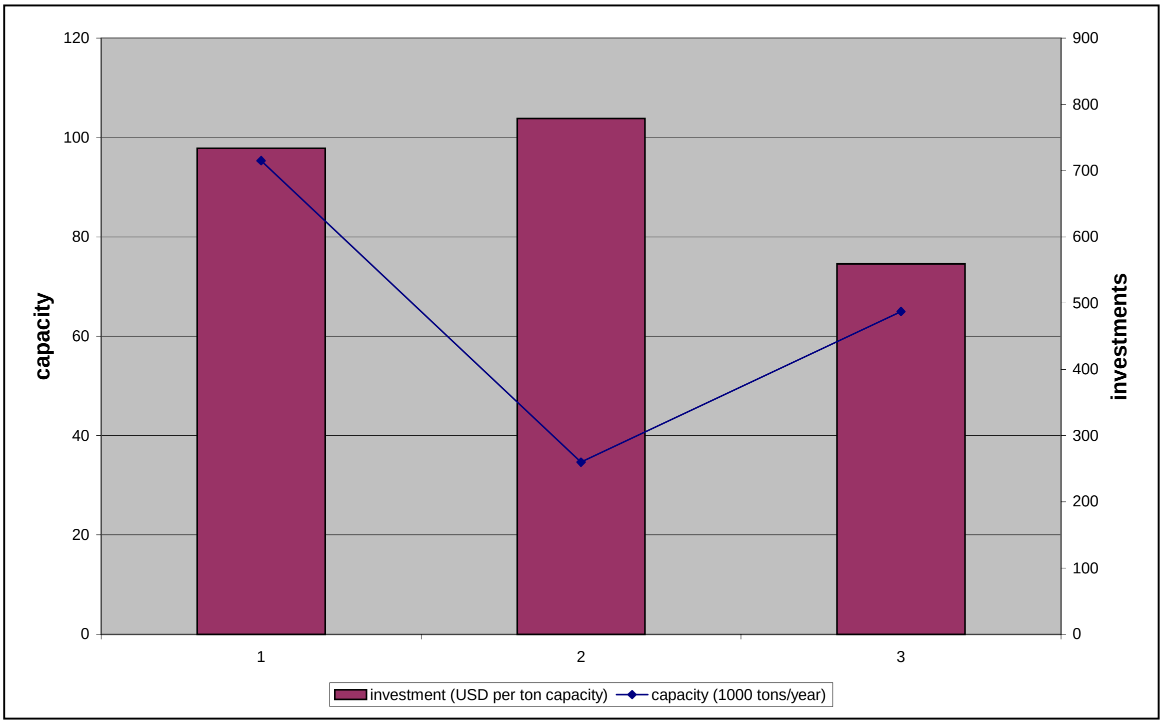

Table 4.10: Technology characterization of the upgrading of waste paper to high quality pulp, using a deinking facility

	2000	2020	2050
Input Resources (tonne)			
waste paper (for graphical paper)	1.4	1.4	1.4
waste paper (for newspaper)	1.2	1.2	1.2
Output (tonne)			
quality I waste paper pulp	1	1	1
quality II waste paper pulp	1	1	1
Energy consumption (GJ/tonne)			
Steam	1.0	1.0	1.0
Electricity (GJe/ton)	2.2	1.1	1.1
Costs (ECU/tonne)			
Investments	734	734	734
other manufacturing costs	41	41	41
o.w. labor	33	33	33
references	McKinney, 1995 PPI, 1997	Cesar and McBride, 1994 Virtanen and Nilsson, 1995	Frenzel, 1995 Janda, 1995

Table 4.10: Technology characterization of the upgrading of waste paper to low quality pulp

	2000	2020	2050
Input Resources (tonne)			
waste paper	1.1	1.1	1.1
Output (tonne)			
Quality III waste paper pulp	1	1	1
Energy consumption (GJ/ton)			
Steam	1.1	1.0	1.0
Electricity (GJe/ton)	1.7	0.9	0.9
Costs (ECU/tonne)			
Investments	550	550	550
other manufacturing costs	31	31	31
labor	24	24	24
references	McKinney, 1995 PPI, 1997	Cesar and McBride, 1994 Virtanen and Nilsson, 1995	Frenzel, 1995 Janda, 1995

5 Production of paper

5.1 Paper products in Europe

The total capacity for producing paper and board products in Europe was 80.8 million tons in 1995. About 30% of the European paper and board production capacity is located in Scandinavia. The top producers are Germany, Finland and France respectively. The production capacity increased with 46% in the period 1986-1995 [PPI, 1997].

The total European consumption in 1995 added up to 66.2 million tons. The largest consumers were Germany, the U.K. and France respectively. Western Europe imported 32.1 and exported 40.7 million tons in 1995.

In Table 5.1 the production and consumption of several paper grades are summarized.

Table 5.1: Production, consumption and trade of paper in Europe (in million tons) [PPI, 1997]

	production	consumption	imports	Exports
Newsprint	9.7	9.1	5.2	5.8
graphic paper	27.8	22.4	13.6	19
Tissue	3.6	3.6	1	1
Packaging paper	27.7	26.1	11.6	13.3

The paper grades in Table 5.1 can be more refined towards specific categories. For example, 10.3 million tons of coated printing and writing paper are produced (graphic papers) and another 10.6 million tons is uncoated. Furthermore 8.6 million tons of graphic paper is wood free, i.e. produced with chemical pulp, of which 3.7 million tons is coated [PPI, 1997].

Packaging paper is a combined category consisting of corrugated materials (11.9 million tons), kraftliner (1 million tons) and board (4.8 million tons) [PPI, 1997].

In the description of the production processes of paper we will only focus on the main grades as stated in Table 5.1. Therefore, we should keep in mind that the description and the presented data are average descriptions and numbers and that large deviations exist within the general paper grades.

5.2 Paper making, general process description

A paper mill consists of three parts: stock preparation, paper machine and finishing.

In the stock preparation stage the pulp is dispersed in 20 times the amount of water (stock). The quality of the stock can be adjusted by adding additives. The stock is then treated in refiners in order to get a good fiber to fiber bonding that is needed for the desired paper quality. The last step in the stock preparation stage is the cleaning of the pulp.

The next stage in the paper mill is the paper machine. Here the water is removed from the stock and the fibers are left in a sheet. The paper machine can be divided in a wet end and a dry end. The wet end is the forming of the sheet. The stock with a consistency of 0.5%-1% is dispersed on a fine wire screen. Then the water is removed leaving a sheet with a consistency of 15-20% (95% of the water is removed).

The dry end consists of a press section and a drying section. In the press section water is squeezed out of the sheet by passing it through multiple pairs of cylinders. The consistency of the sheet increases to 40-50% (1-2% of the initial water is removed).

The drying section consists of 40-60 steam heated cylinders. Water in the sheet is removed by evaporation. The consistency of the sheet after drying is about 94% (1% of the initial water is removed in this step).

The finishing stage consists of smoothing the surface of the paper products, wounding it on reels, cutting, packing and dispatching.

5.3 Production of newsprint

The main production facilities for the production of newsprint are located in Scandinavia (4.7 millions tons) and Germany (1.7 million tons) [PPI, 1997].

Newsprint can be produced using virgin wood pulp (mostly mechanical pulp) or waste paper pulp or any combination of the two. Recently, some new facilities are built to produce newsprint from 100% recycled fibers [PPI, 1997].

Newsprint can be produced in an integrated mill and a non-integrated mill. For modeling purposes we assume that the integrated mill uses 100% wood as feedstock and that the non-integrated mill can vary the feedstock between 100% mechanical pulp and 100% secondary pulp.

Energy and costs data for newsprint production

In Nilsson (1995) two Newsprint mills are modeled, one for 1990 and one for 2000. The two mill are integrated mills. The 1990 model uses 7.6GJ_{el} and 3.36 GJ steam. The 2000 mill used less energy: 5.4 GJ_{el} and 2.33 GJ steam.

The integrated mill modeled in Table 5.3 is based on these figures. In Nilsson (1995) both the electricity and the steam demand is calculated. A part of the steam demand however can be fulfilled by steam recovery from the pulping process. We assumed a 32% recovery for 1990 (Swedish average in 1988) and a 50% steam recovery in 2000.

In the Table 10 an integrated mill is modeled for the production of newsprint and in Table 11 a non-integrated mill is modeled. An integrated paper mill produces pulp and paper within the same facility. The advantage of an integrated mill is that steam recovered from the pulping process can be used to dry the produced paper.

The feedstock of the integrated mill consists entirely of wood.

The non-integrated mill uses a mixture of TMP pulp and waste paper pulp as feedstock. We modeled maximum waste paper inputs for different target years. The total pulp input is 1.02 tons of pulp per ton of paper output. Less energy is needed for making pulp out of waste paper than for producing TMP. Differences in waste paper consumption will therefore affect the total energy consumption of Newsprint production. The energy demand of the paper machine is assumed to remain constant.

Costs of newsprint production

The costs for the production of newsprint are hard to estimate because large differences in investment costs are reported. In PPI (1997) the investments of the Japanese company DAIO are stated. DAIO ordered liner and a newsprint line with a total capacity of 250,000 tons per year for $250 million ($993 per ton). An other Japanese company ordered a very expensive newsprint machine which will cost 2025 per ton capacity [PPI, 1997]. Finally, Svenska ordered a 280.000 ton newsprint mill for $400 million ($1441 per ton capacity) that will be placed in Great Britain. In Ronilla (1995) an investment of $1406 per ton is used as an estimate for the Finnish situation. This corresponds well with the Svenska investment and therefore we will use the Svenska number as an estimate for the average investments costs for newsprint production.

The investment costs mentioned above are valid for paper machines and not for integrated mills. An integrated mill can be based on 100% waste paper and needs therefore a deinking plant, it can be based on 100% TMP and needs therefore a mechanical pulping unit, or it can be based on a combination of the two inputs. The investment costs of an integrated mill will therefore be dependent of the input. For now, we will take the average investment costs of a TMP mill and a waste paper upgrading mill and add this to the investment costs of the paper machine.

Figure 5.1: Investment costs and capacity of several newsprint mills [PPI, 1997, Ronilla, 1995]

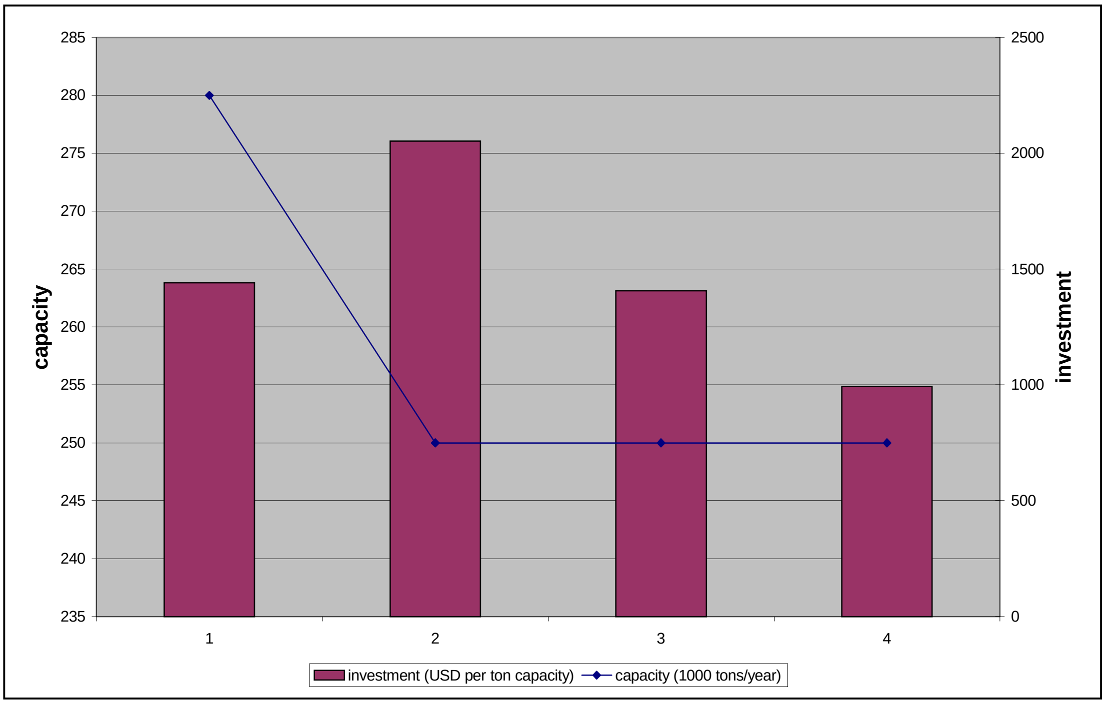

Table 5.2: Technology characterization of the production of newsprint with an integrated paper mill

	2000	2020	2050
Input Resources (tonne)			
wood	1.1	1.1	1.1
Output (tonne)			
Newsprint	1	1	1
Energy consumption (GJ/tonne)			
Steam	0.7	-1.2	-1.2
Electricity (GJe/ton)	8.2	7.0	7.0
Costs (ECU/tonne)			
Investments (ECU/ton capacity)	1958	1958	1958
O&M	109	109	109
o.w labor	87	87	87
reference	van Heijningen, 1992 Ince, 1994	Nilsson, 1995 PPI, 1997	

Table 5.3: Technology characterization of the production of newsprint with a non-integrated paper mill

	2000	2020	2050
Input Resources (tonne)			
pulp	1.02	1.02	1.02
o.w. mechanical pulp	0-100%	0-100%	0-100%
o.w. grade II waste paper pulp	0-100%	0-100%	0-100%
Output (tonne)			
Newspaper	1	1	1
Energy consumption (GJ/ton)			
Fuel			
Steam	2.3	2.3	2.3
Electricity (GJe/ton)	1.5	1.5	1.5
Costs (ECU/tonne)			
Investments	1441	1441	1441
O&M	80	80	80
o.w labor	64	64	64
reference	van Heijningen, 1992 PPI, 1997	Nilsson, 1995	

5.4 The production of writing and printing paper

The category graphic papers or printing and writing paper is a wide category. It contains uncoated and coated woodfrees, lightweight coated (LWC) paper and supercalendered (SC) paper. Woodfree paper is paper that is free from mechanical pulp but in practice it means that the paper sheet should contain less than 10% mechanical pulp. LWC is a paper type that can be categorized as paper that consists of 45-75% of mechanical pulp (besides chemical pulp) and is coated. SC paper is an uncoated mechanical paper which has acquired its printability by filler addition and supercalendering.

As also seen in the beginning of this chapter, the woodfree papers have a market share of more than 30% of the graphical paper production in Europe[PPI, 1997].

The product category ‘printing and writing paper’ is diverse. This also holds for the reported energy consumption figures. We assumed that the Finnish data from Komppa (1993) are representative for Europe. For the situation in 1990 we used the specific energy consumption of a higher paper grade than for the 2000 situation (coated fine paper versus office paper) in order to simulate an increase in energy efficiency over the years.

The investment costs for the production of graphical paper grades vary strongly. This is logical because large differences in product quality are possible. For instance, paper can be coated or uncoated. A coating line with a capacity of 120,000 tons per year costs around $25 million [PPI, 1997]. Graphical paper can also be bleached or unbleached. A bleach line costs around $173 per ton capacity. In PPI (1996) and PPI (1997) the orders of several paper machines for the production of graphical paper are mentioned. Figure.. gives an overview of the investment costs per ton capacity and the total capacity of the mills. The average investment per ton is $1157. We will use this number as an estimate for the investment costs for the production of graphical paper.

The other manufacturing costs are taken from Ince (1994) just like the labor input per ton. The input data for the Markal model are stated in Table 12 and 13.

For the integrated mill it is harder to give a good estimate of the investment costs. Not only the investments for the paper machine may vary, also the investments of the pulping line can differ dramatically. This is especially the case when waste paper is considered as feedstock instead of chemical pulp. Up till now, waste paper is hardly used as a feedstock for graphical paper qualities. We will therefore add the investment costs for chemical pulp and for the paper machine to estimate the total investments of an integrated mill. In future years a larger input of waste paper can be expected in the production of graphical paper. This trend can be modeled by the non-integrated mill.

We modeled a non-integrated paper mill that produces writing and printing paper using chemical pulp and fillings as feedstock. For different target years a maximum input of waste paper pulp is defined.

Figure 5.2, Investment costs and capacity of several graphical paper mills [PPI, 1996, PPI, 1997]

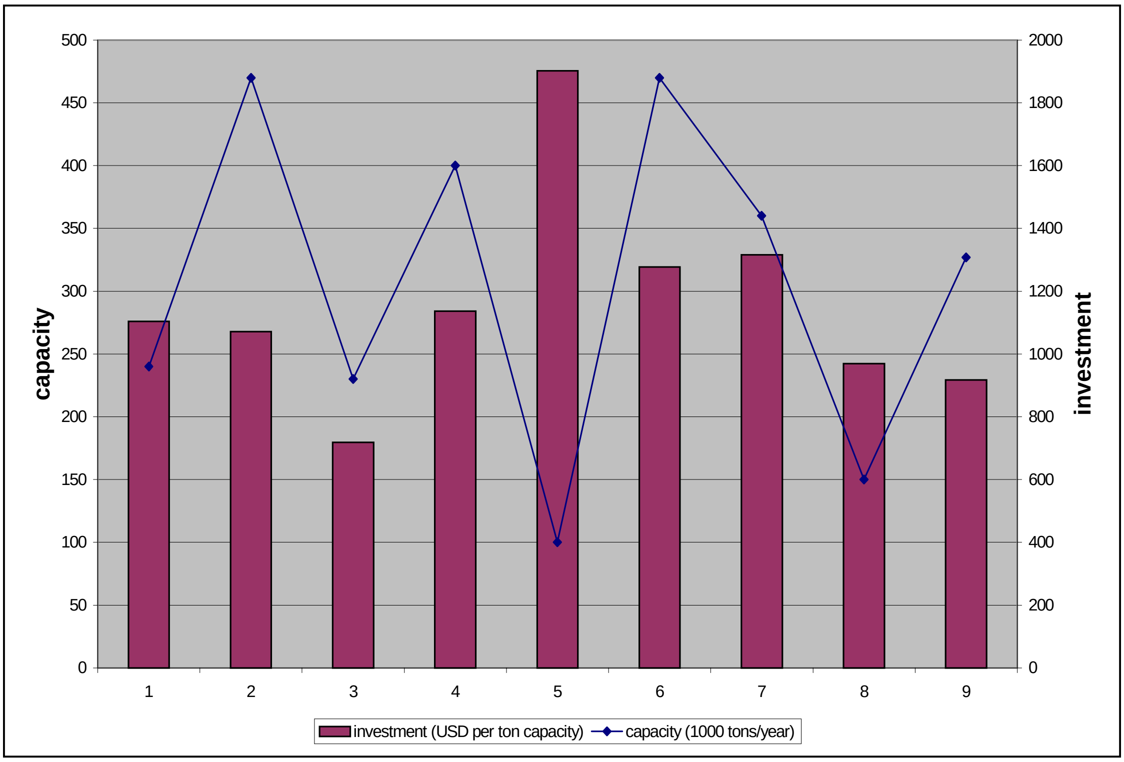

Table 5.3: Technology characterization of the production of printing and writing paper with an integrated paper mill.

	2000	2020	2050
Input Resources (tonne)			
wood	1.3	1.3	1.3
fillings	0.14	0.14	0.14
Output (tonne)			
Graphical paper	1	1	1
Black liquor (GJ)	11.5	11.5	11.5
Bark (GJ)	2	2	2
Energy consumption (GJ/tonne)			
Steam	11.4	11.4	11.4
Electricity (GJe/ton)	4.0	4.0	4.0
Costs (ECU/tonne)			
Investments	1828	1828	1828
O&M	102	102	102
o.w labor	81	81	81
Reference	Komppa, 1993	van Heijningen, 1992	PPI, 1997

Table 5.4: Technology characterization of the production of printing and writing paper with a non-integrated paper mill.

	2000	2020	2050
Input Resources (tonne)			
Pulp	0.77	0.77	0.77
o.w. chemical	45 - 50%	40 - 50%	40 - 50%
o.w. TMP	50%	40 - 50%	40 - 50%
o.w. grade I waste paper pulp	0 - 5%	0 - 20%	0 - 20%
Fillings	0.27	0.27	0.27
Output (tonne)			
Graphical paper	1	1	1
Energy consumption (GJ/tonne)			
Steam	7.0	7.0	7.0
Electricity (GJe/ton)	2.5	2.5	2.5
Costs (ECU/tonne)			
Investments	1157	1157	1157
O&M	64	64	64
o.w labor	51	51	51
Reference	Komppa, 1993	van Heijningen, 1992	

5.5 Production of packaging paper

Packaging paper is just like printing and writing paper also a diverse product category. It contains different packaging paper grades and also cardboard products. Germany, Sweden and Italy are the top three paper and board packaging producers in Western Europe.

According to Komppa (1993) the production of folding boxboard (cardboard type) has a higher energy demand than brown kraftliner (paper type). We assumed that the data for cardboard are representative for the average European situation in 1990 while the kraftliner data are representative for the European situation in 2000.

Depending on the packaging paper type different shares of waste paper are used in the production process. Only for the Netherlands this varies between 100% for corrugated board and 72% for packaging paper [VNP, 1995]. In the factsheets a mill is modeled which uses a maximum of 75% waste paper in 1990 and higher shares are assumed to be reachable for future target years. Furthermore different virgin wood pulp types are used for the production of different packaging paper grades. Because we did not define different packaging products we will model chemical pulp as the only virgin pulp used in the process.

The investment costs for the production of packaging paper depends heavily on the paper type produced. In PPI (1996) and PPI (1997) orders of 5 packaging paper machines are described. In figure 5.3 these orders are compared. It shows that the investment costs vary between $900 per ton capacity and $1280 per ton capacity. The average investment costs are $1085 per ton capacity. We will use this as the estimate for the average investment costs for the production of packaging paper.

For an estimate of the investment costs of an integrated mill, the same problems hold as for graphical paper. It is already common to produce linerboard based on 100% recycled paper and on the other hand some grades are based on 100% chemical pulp. For modeling purposes we define the integrated mill as a combination of a paper machine and a kraft pulp mill that produces unbleached kraft pulp. Therefore we will extract $173 per ton capacity from the kraft pulping investment costs and add this to the paper machine investment costs. The other manufacturing costs are based on Ince (1994), just like the labor input.

Figure 5.3: Investment costs and capacity of several packaging paper machines [PPI, 1996 and PPI, 1997]

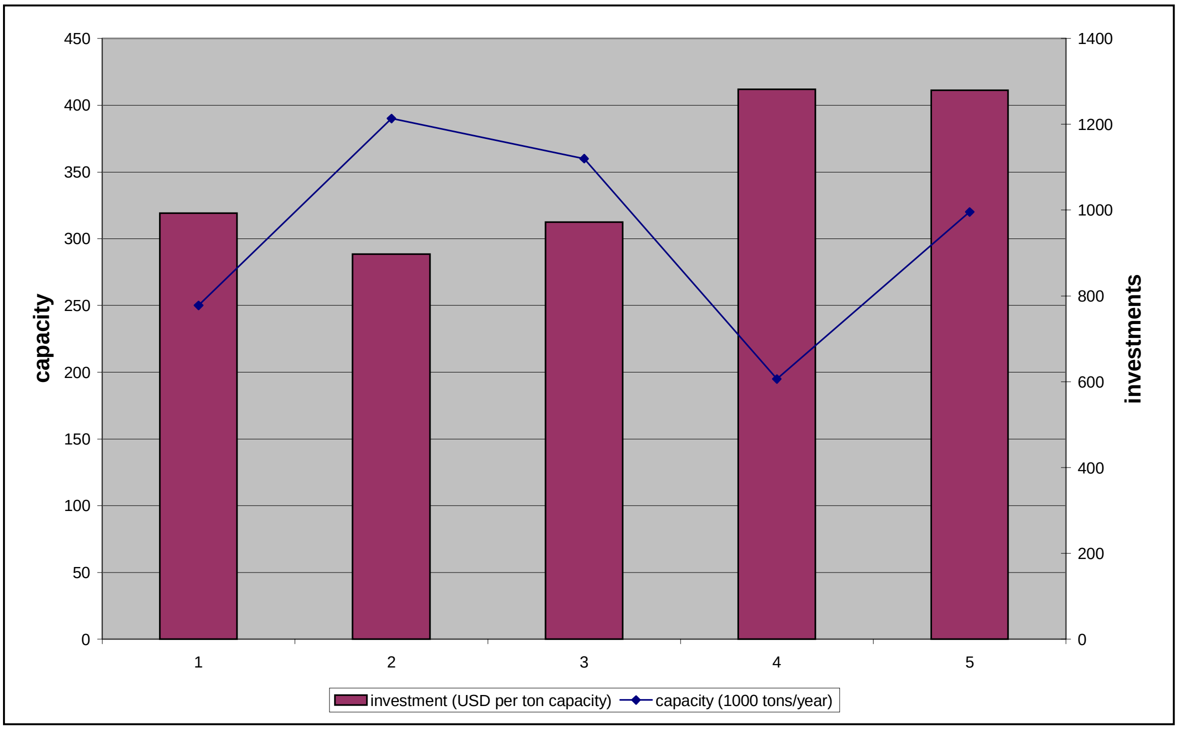

Table 5.5: Technology characterization of the production of packaging paper with a non-integrated paper mill.

	2000	2020	2050
Input Resources (tonne)			
Pulp	1.02	1.02	1.02
o.w. chemical pulp	0 - 100%	0 - 100%	0 - 100%
o.w. grade II waste paper pulp	0 - 75%	0 - 85%	0 - 90%
o.w. grade III waste paper pulp	0 - 25%	0 - 25%	0 - 25%
Output (tonne)			
Packaging paper	1	1	1
Energy consumption (GJ/tonne)			
Steam	6.0	6.0	6.0
Electricity (GJe/ton)	1.8	1.8	1.8
Costs (ECU/tonne)			
Investments	1058	1058	1058
O&M	59	59	59
o.w labor	47	47	47
reference	Komppa, 1993	van Heijningen 1992	Ince, 1994

Table 5.6: Technology characterization of the production of packaging paper with an integrated mill.

	2000	2020	2050
Input Resources (tonne)			
wood	2.04	2.04	2.04
Output (tonne)			
Packaging paper	1	1	1
Black liquor (GJ)	23	23	23
Bark (GJ)	4	4	4
Energy consumption (GJ/tonne)			
Steam	11.7	11.7	11.7
Electricity (GJe/ton)	3.7	3.7	3.7
Costs (ECU/tonne)			
Investments	2413	2413	2413
O&M	134	134	134
o.w labor	107	107	107
reference	komppa, 1993 PPI, 1997	van Heijningen 1992	Ince, 1994

5.6 The production of sanitary paper

Sanitary paper or tissue is the smallest of the categories as defined in the beginning of this chapter. To produce tissue, high standards need to be met. Tissue paper needs to be soft, hygienic and fairly strong. To produce tissue with such qualities, kraft pulp is often used as feedstock. Also deinked waste paper can be used for the production of tissue. According to van Heijningen (1992) 0.71 ton chemical pulp and 0.43 ton waste paper is used on average to produce a ton of tissue paper.

For 2000 we assume that a waste paper input of 100% is technically possible because already some tissue mills use 100% waste paper as feedstock [PPI, 1997].

Komppa (1993) states the energy demand of the production process for tissue. According to him 7.0 GJ steam and 3.6 GJ_{el} is needed for the production of a ton sanitary paper. Melman (1990) states the realized minimum in the Netherlands at 5.3 GJ steam and 2.4 GJ_{el}.

To estimate the investment costs of a paper mill for tissue production, two sources are available. PPI (1997) states that Kimberly Clark, the largest producer of tissue, ordered a paper machine with a capacity of 68,000 tons per year. The costs were $172 million. This means an investment of $2500 per ton capacity. This is a very large number compared to investment costs of other paper machines. This number seems too high for an average tissue machine.

In Ronnila (1995) an average investment cost of $1705 per ton capacity is estimated. This number seems to more in line with the investment costs of the other paper grades.

Table 5.7: Technology characterization of the production of sanitary paper with a non-integrated mill.

	2000	2020	2050
Input Resources (tonne)			
pulp	1.14	1.14	1.14
o.w. chemical pulp	0 - 100%	0 - 100%	0 - 100%
o.w. grade II waste paper pulp	0 - 100%	0 - 100%	0 - 100%
Output (tonne)			
Sanitary paper	1	1	1
Energy consumption (GJ/tonne)			
Steam	5.3	5.3	5.3
Electricity (GJe/ton)	2.4	2.4	2.4
Costs (ECU/tonne)			
Investments	1705	1705	1705
O&M	95	95	95
o.w labor	76	76	76
reference	komppa, 1993 Ince, 1994	van Heijningen, 1992	PPI, 1997

Table 5.8: Technology characterization of the production of sanitary paper with an integrated mill.

	2000	2020	2050
Input Resources (tonne)			
wood	2.3	2.3	2.3
Output (tonne)			
Sanitary paper	1	1	1
Black liquor (GJ)	23	23	23
Bark (GJ)	4	4	4
Energy consumption (GJ/tonne)			
Steam	12.6	12.6	12.6
Electricity (GJe/ton)	4.6	4.6	4.6
Costs (ECU/tonne)			
Investments	3205	3205	3205
O&M	178	178	178
o.w labor	142	142	142
reference	komppa, 1993 van Heijningen, 1992	melman, 1990 PPI, 1997	Ince, 1994

5.7 The production of other paper.

Other paper include photographic paper, construction paper and paperboard, special thin paper and many other paper products. No energy and cost data are available for this category. We assumed that the energy efficiency will be between the categories packaging paper and writing and printing paper. We will use a maximum recycled paper content of 50% in 1990 and higher shares in future target years. Also for determining the costs we have taken an average between packaging and writing and printing paper.

Table 5.9: Technology characterization of the production of other paper and board using a non-integrated mill

	2000	2020	2050
Input Resources (tonne)			
pulp	1.02	1.02	1.02
o.w. chemical pulp	0 - 100%	0 - 100%	0 - 100%
o.w grade II waste paper pulp	0 - 45%	0 - 55%	0 - 55%
Output (tonne)			
Other paper	1	1	1
Energy consumption (GJ/tonne)			
Steam	6.5	6.5	6.5
Electricity (GJe/ton)	2.2	2.2	2.2
Costs (ECU/tonne)			
Investments	1108	1108	1108
O&M	62	62	62
o.w labor	49	49	49
Reference	see 'packaging paper' and 'writing and printing paper'		

Table 5.10: Technology characterization of other paper and board production using an integrated mill

	2000	2020	2050
Input Resources (tonne)			
wood	1.7	1.7	1.7
Fillings	0.1	0.1	0.1
Output (tonne)			
Other paper	1	1	1
Black liquor (GJ)	17	17	17
Bark (GJ)	3	3	3
Energy consumption (GJ/tonne)			
Steam	12.3	12.3	12.3
Electricity (GJe/ton)	4.1	4.1	4.1
Costs (ECU/tonne)			
Investments	2121	2121	2121
O&M	106	106	106
o.w labor	85	85	85
reference	see 'packaging paper' and 'writing and printing paper'		

6 New technologies in paper making

The drying step in the paper machine is the least energy efficient operation. Only 1% of the initial water is removed while it uses 90% of the total heat demand of the paper machine [de Beer et al., 1993]. Long term energy conservation can be reached by several different techniques which reduce the steam consumption of the drying process.

The techniques are based on different principles. Firstly it may be possible to form the sheet with a minimum of water (dry sheet forming, high consistency forming). Secondly, it may be possible to improve the pressing section and drying section so less steam is needed for drying (impulse drying, condebelt drying, press drying, air impingement drying). Finally it may be possible to make use of the latent heat of the evaporated moisture (steam impingement drying, airless drying).

For future paper making we selected a few technologies that are likely to overcome the current barriers in their development and will obtain a significant market share. These techniques are impulse drying, condebelt drying, air impingement drying and steam impingement drying.

For all these techniques we assumed no change in the cost data because these techniques will penetrate into the market for other reasons than energy efficiency. These techniques are supposed to be a cost-effective alternative for current paper production and will have a positive influence on the paper quality produced.

6.1 Penetration of the new techniques

It is always hard to make a good estimate for the expected degree of market penetration for the new techniques. The actual penetration into the market is influenced by many factors. Here we define the market penetration as technical penetration which means that when a technique is developed completely, it has a technical penetration potential of 100%. To estimate the penetration in 2020 and 2050 we assumed a lifetime of the current machinery of 30 years. So every year 3.3% of the capacity can technically be replaced with new techniques.

For impulse drying we estimated that the technique would be completely developed in 2010. So from that time on market penetration is possible. In 2020 33% of the machinery can be replaced so the technical degree of penetration is 33%. For the other new techniques we estimated that complete development will be reached in 2005. So in 2020 we calculated a penetration of 50%. In 2050 all techniques have a technical degree of penetration of 100%.

6.2 Condebelt drying

Condebelt drying (or condensing belt drying) is a technique where the wet web is carried between two steel bands, one hot band and one cold band, and subjected to high pressure and temperature. The method is characterized by absence of air in the drying zone and a long dwell time [de Beer, 1993]. The drying rate is 5-15 times as high as conventional drying, resulting in a much shorter drying section. The technology is being developed because it can improve the paper quality control. The process is applicable to all paper making processes except tissue. Currently the method is in a pilot plant stage at Valmet Tampella in Finland. Using condebelt drying savings in steam consumption are estimated at 26% for the entire paper machine[de Beer, 1993, Smit et al. 1994]. The savings on electricity is negligible because the drying section only uses 2% of the total electricity consumption. The investment costs are high but due to a heavily reduced drying section the net investments are assumed to be negligible. The method is assumed to be commercially available in 2005.

In Annex I the influence of this technology on the energy demand of the paper machines as defined in chapter 5 is illustrated.

Table 6.1: Change in energy consumption and investments costs due to using the condebelt process. The energy and the cost data are expressed as changes with respect to the data of the reference production processes.

	2000	2020	2050
Change in Energy consumption (%)			
Fuel			
Steam	-20	-20	-20
Electricity	0	0	0
Change in costs (%)			
Investments	0	0	0
O&M	0	0	0
penetration (%)	0	50	100
reference	de Beer et al., 1993 de Beer et al., 1997		Smit et al., 1994

6.3 Impulse drying

Impulse drying is another promising technique that is currently being developed. In impulse drying the sheet is pressed against a nip by a very hot role. A very short contact time is used. Depending on the desired temperature the cylinders are heated with steam or electro-techniques (infrared, induction). Due to the improved dewatering of the sheet the drying section can be significantly reduced. Impulse drying is being developed because it is expected that it will improve paper quality.

Impulse drying will decrease steam demand of the paper machine by approximately 50% - 75%. We will assume a saving of 60%. It will increase electricity demand by about 5 - 10% [de Beer, 1998]. We will assume an increase of 8%.

In Annex I the influence of this technology on the energy demand of the paper machines as defined in chapter 5 is illustrated.

Table 6.2: Change in energy consumption and investments costs due to using impulse drying technology. The energy and the cost data are expressed as changes with respect to the data of the reference production processes.

	2000	**2020**	**2050**
Change in Energy consumption (%)			
Fuel			
Steam	-60	-60	-60
Electricity	8	8	8
Change in costs (%)			
Investments	0	0	0
O&M	0	0	0
Penetration (%)	0	33	100
Reference	de Beer et al., 1993 de Beer et al., 1998		

6.5 Air impingement drying

Air impingement drying involves blowing hot air at high velocity against the wet paper sheet. This technique is developed to obtain higher drying rates but the energy demand can be lower than with conventional drying techniques. The technology has already been applied for sanitary paper and is now being developed for other paper types. The expected saving on steam demand are 10% - 40% and the electricity consumption will probably increase with 0% - 5% [de Beer, 1998]. We will assume a steam saving of 25% and an increase in electricity consumption of 3%.

In Annex I the influence of this technology on the energy demand of the paper machines as defined in chapter 5 is illustrated.

Table 6.3: Change in energy consumption and investments costs due to using air impingement drying technology. The energy and the cost data are expressed as changes with respect to the data of the reference production processes.

	2000	2020	2050
Change in Energy consumption (%)			
Fuel			
Steam	-25	-25	-25
Electricity	3	3	3
Change in costs (%)			
Investments	0	0	0
O&M	0	0	0
Penetration (%)	0	50	100
Reference	de Beer et al., 1993		de Beer et al., 1998

6.5 Steam impingement drying

The last technology uses the latent heat of the evaporated water: steam impingement drying. This technology is comparable to air impingement drying but in this case super heated steam is used as the drying medium instead of hot air. The steam (300 °C) evaporates the water so more steam at lower temperature is produced (150 °C). The low temperature steam is upgraded to 300 °C again and used for the drying process. Several steam impingement driers can totally replace the entire conventional drying section. The investment costs are therefore lower or equal to a conventional paper machine. A reduction of the heat demand of 10 - 15% and also a reduction of the electricity demand of 5 - 10% is expected [de Beer, 1997]. We will assume a heat reduction of 13% and an electricity reduction of 7%.

In Annex I the influence of this technology on the energy demand of the paper machines as defined in chapter 5 is illustrated.

Table 6.4: Change in energy consumption and investments costs due to using steam impingement drying technology. The energy and the cost data are expressed as changes with respect to the data of the reference production processes.

	2000	2020	2050
Change in Energy consumption (%)			
Fuel			
Steam	-13	-13	-13
Electricity	-8	-8	-8
Change in costs (%)			
Investments	0	0	0
O&M	0	0	0
penetration (%)	0	50	100
reference	de Beer et al., 1993		de Beer et al., 1997

6.6. Advanced drying

A combination of short term and long term options as described above may lead to even larger improvements in energy efficiency, resulting in lower specific energy consumption figures as would follow from the tables 6.1 to 6.4. In de Beer (1998) it is estimated that on the long term the steam consumption can be reduced by 75 - 90% without an increase in electricity consumption. A possible way to reach these reductions is a combination of impulse drying, steam impingement drying and a number of small improvements. The costs of this paper machine configuration will be less than current configurations.

7. Production of other Natural Organic Materials

Wood and paper products are the most important natural organic materials when the consumption is taken into account. For the MARKAL model three other materials will be modeled : compost, biopolymers, natural rubber.

7.1 Compost

Compost is used for cultivation of vegetables and flowers. Furthermore, significant amounts are used for gardening purposes and soil improvement. Compost is made from dried peat with some additives like limestone. Peat is considered to be a fossil fuel and therefore the use of compost which oxidises in the top soil implies a emission of CO_2. In Gielen and Okken (1994) a peat content of 90% is assumed for compost which leads to a CO_2 emission of 2.3 ton per ton compost.

In van Duin (1997) the estimated end use of peat in Europe is estimated at 4 Mtonnes in 2000.

An alternative for compost from peat is the use of compost from biomass waste. The latter can either be garden and kitchen waste or organic waste from auctions and agricultural activities. The advantage of the agricultural and auction waste is that these waste streams are generally cleaner than kitchen waste.

In the Netherlands a lot of experience has been gained with composting organic kitchen waste. These experiences learned that the waste streams are often polluted with all kinds of materials that can not be composted and generally have negative effects on the quality of the compost.

However, we assume that the availability of clean organic waste is no problem to fulfill the entire demand for compost.

The production of compost from organic waste can either be a anaerobic process or a aerobic process. The advantage of anaerobic digestion is that the methane emissions during the digestion process are used for energy recovery purposes. The aerobic process does not recover methane but the advantage of this process is that is generally cheaper than the anaerobic process.

Table 7.1: Energy, CO_2 and cost data for the production of compost.

	Peat	Anaerobic Digestion	Aerobic digestion
Input resources (tonne/tonne)			
Peat	0.9		
organic waste		0.5	0.5
Energy consumption (GJ/tonne)			
Fuel (methane)		-1.6	
Steam			
Electricity (GJel./tonne)		0.2	0.1
CO_2-emission (tonne/tonne)	2.3		
Costs (ECU/tonne)	20	56	46

In Hekkert (1995) these processes are described in detail including energy consumption and costs. An overview of these data is given in Table 7.1.

In Table 7.1 the production costs for compost made from peat are estimated at 20 ECU per tonne. The costs are expected to be much lower than the digestion processes because the process is only involves some mixing with other materials. Costs of collecting organic waste and production of peat are not considered.

7.2 Biopolymers

Biopolymers or bioplastics can often be used as a substitute for normal plastics that are made out of oil. The use of biopolymers has a few advantages over the use of normal plastics. The first advantage is that biopolymers can easily be broken down by nature when they are turned into waste. For normal plastics these processes take a very long time. From a waste management point of view this might be reason for using bioplastics especially for short life products that are often thrown away like six pack rings, golf ball pins and different types of packaging [Remijn, 1997].

An other advantage that is more relevant in for modeling in MARKAL is the renewability of the feedstock. Contrary to the fossil fuels used for plastics production, the feedstock for biopolymers are renewable which can have large effect on the CO_2 emission of the products. Renewable feedstock has no net CO_2 emission because the CO_2 cycle is closed: the crops take up the same amount of CO_2 during their growth as the amount emitted during the waste stage. The only extra CO_2 that is emitted in the waste stage is the input of energy necessary in the production phase of the products.

Biopolymers can be made from starch and cellulose or by means of bacteria. The latter leads to polymers that are made from polyhydroxyalkanoates (PHA) that are accumulate in a wide variety of bacteria [Poirier *et al*., 1995]. Examples of polymers made this way are polylacticacid and polyhydroxybutyrate polymers that are used in the medical sector (implants) and in the packaging sector. Biopol is well known biopolymer made by Zeneca that is used for paper coating and packaging products.

Starch based biopolymers can be made from wheat, corn, potatoes and rice. Depending on the crop the size and the shape of the starch granulates differ [Fritz *et al*., 1994]. Cellulose based biopolymers are made from sulfite woodpulp. Cellulose by itself is not suitable for biopolymer production and therefore it is modified to cellulose nitrate or cellulose acetate [Fritz et al., 1994].

For the MARKAL model we will not model all three types of biopolymers. Starch based biopolymers are the cheapest and therefore closest to implementation in MARKAL modeling terms. In reality the costs of the biopolymer are not the only aspect which determines the demand. Starch based polymers for example are highly susceptible for water and therefore have limited application possibilities. Biopolymers like biopol do not have this problem. Also starch derived biopolymers (starch-acetate) are insensitive to water. For MARKAL modeling we will therefore model two types of biopolymers. A cheap biopolymer with limited application possibilities and a biopolymer that is more expensive but can be used for almost all applications. We furthermore assume that bioplastics granulate can be processed in exactly the same ways as conventional plastics and that no extra costs in this stage of production are necessary.

Costs of biopolymer production

Starch based bioplastics have currently a production cost that varies between 1.8 and 4.0 ECU per kilogram. The current production costs of PHA polymers are 6 ECU per kg but upscaling of equipment will lead to a price of 5 ECU per kg [van Onck, 1996].

For comparison, PE granulate costs about 0.6 ECU per kg. In Raaijmakers (1996) it is estimated that starch based biopolymers will drop in price and eventually cost about 0.9 ECU. For the MARKAL model we will model for 2020 two types of biopolymers. The cheap biopolymer has a production cost of 0.9 ECU per kg while the expensive biopolymer costs 4 ECU per kg. We estimate that the cheap biopolymers can only replace 5% of the normal plastics and that the expensive biopolymers can replace all plastics that are currently used.

Energy use during production

To model biopolymers next to normal plastic we need to create insight in the energy consumption during production. No exact energy data are available for these processes. We will therefore compare the production of bioplastics with conventional plastics production. For normal plastics the energy consumption during production is necessary for cracking of crude oil, naphta cracking, separation of fractions and polymerization. For biopolymer production many of these steps are not necessary. Starch by itself is already a polymer and the only processes needed are separation from the crop and extrusion in a twin screw extruder [Selke, 1996]. In the case of biopolymer production with bacteria also complete polymers are produced and only extraction and extrusion are needed. In order to estimate the energy consumption of the production process we will use assume that the same energy consumption for extrusion of LDPE holds for biopolymers. Based on Gasselseder et al. (1992) and Beer and Worrell (1991) we estimate the energy consumption of the extrusion process at 0.4 GJ_{el} per tonne. Furthermore we assume that some additional energy is needed for various processes (crop cleaning and swelling, grinding, fibre, sand and gluten removal, starch refining and starch drying [Fritz et al., 1994]) which we estimate at 0.4 GJ_{el} per tonne. In table 7.2 these data are summarized. We have assumed an efficiency of 85% for biopolymer production from starch and assume a dry matter content of potatoes of 80%. A lower efficiency (30%) for the PHA biopolymers is assumed [Poirier et al., 1995].

We need to take into account that production of biopolymer is still a small scale business where many new developments are possible. One of these development for example is the use of genetic engineered crops that may produce PHA polymers at a cost of ECU 500 per tonne [Poirier, 1995]. It would therefore be wise to work with different scenario's in the MARKAL model in which the development of biopolymers can be varied. Table 7.2 only states the technology characterization in 2000.

Table 7.2: Technology characterization of biopolymer production in 2000.

	Starch biopolymer	PHA biopolymer
Input		
Potatoes (tonne/tonne)	1.5	
Glucose (tonne/tonne)[4]		3.3
Energy		
Electricity (GJ/tonne)	0.8	0.8
costs (ECU/tonne)	900	4000

7.3 Natural rubber

We will model natural rubber for the MARKAL model because it is a natural substitute for synthetic rubber which has the same advantages in CO_2 emission as described in the previous paragraph. The synthetic rubbers will be modeled in Joosten and Worrell (1998) by means of SBR (Styrene-Butadiene-Rubber) which is the most used synthetic rubber type.

[4] A price of 0.55 ECU per kg glucose leads to a material input cost of 1800 ECU per tonne. For comparison, starch from corn has a market price of 250 ECU per tonne [Poirier et al., 1995]

The total amount of rubber used globally is estimated at 15.6 million tonnes. The consumption in Western Europe is 3.2 million tonnes [Anon., 1997].

The rubber consumption can be divided in two groups: natural rubber and synthetic rubber. In 1996 about 38 percent of the global rubber consumption was natural rubber. For Europe this proportion was a little different: 29 percent (or 948 million tonnes) of natural rubber was used [Anon., 1997].

More than 50% of the global rubber consumption in 2000 is expected to be used for the production of tires [Anon., 1996a].

Natural Rubber is mainly produced in Asia. About 95% of the world production is produced in this region. The main Asian producers are Indonesia, Malaysia, and Thailand which have a joint share of 75% of the global production [Anon., 1996b].

About 200 tree species are capable of producing natural rubber. Currently the tree Hevea Brasiliences is used for over 99% of the global production. The trees are grown in commercial fields and typical annual yields are 2000 - 2500 kg / ha. Experimental yields of 4000 kg/ha have been recorded and the theoretical maximum is believed to be 9000 kg/ha [Kirk Othmer, 1982].

The natural Latex is harvested from the trees by a process called tapping which stands for controlled wounding of the trees. After harvesting the latex is taken to a mill where it is further processed.

Depending on the desired properties the latex is just concentrated or it is further processed to produce dry rubber. Typical production steps are plastification and vulcanization. The latter is the process of mixing the rubber with sulfur in order to increase the elastic and mechanical properties of the rubber.

To estimate the energy consumption for natural rubber production no other sources are available than Hoi and Bridgwater (1989) in which the energy consumption is stated at 26.3 GJ_{prim} per tonne. Wood is used as fuel (1.75 kg wood per kg rubber). Furthermore, transportation adds another 2.1 GJ_{prim} per tonne rubber [Worrell and de Beer, 1993].

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