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Environmental best practices in the forest cluster

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Approved by

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Abstract

This study deals with the forest cluster of the European Union (EU) and aims at giving an overview of environmental best practices. Economy is stressed in the discussion on environmental practices. Strategies for the future and the age of the target plant also play an important role when defining best practices. Emissions of volatile organic compounds (VOCs) from the cluster as a whole and emissions to water from the pulp and paper industry are one of the biggest environmental concerns in the forest cluster. The printing industry appears to have the greatest potential to improve its environmental performance. Furthermore, on the papermaking side, a high potential for improvement of the environmental performance is related to dematerialization, which is one of the most neglected environmental issues in the paper industry. A possible analytical tool for comparing the environmental impact of virgin fiber and recycled fiber is briefly described.

About the Author

Marko Salo participated in IIASA's Young Scientists Summer Programme in 1999. He worked in the Sustainable Boreal Forest Resources Project (FRP). This document is a background report for the possible future activities of FRP. Mr. Salo works as a researcher at the corporate R&D department of Metsä-Serla Group, Finland. The company is one of the largest pulp and paper producers in the Europe.

Environmental best practices in the forest cluster

Marko Salo

1. Introduction

1.1 Background

If interaction between different industry branches is particularly intense and if strong synergies exist, the group of branches can be called a cluster (Hernesniemi et al. 1996). The forest cluster consists of

- forest-based industries, which use forests as a resource,
- speciality input and machinery industries, which provide machines, other inputs, and resources for the primary goods producers,
- associated services providing transportation and other nonmaterial inputs,
- buyers of the primary goods.

The environmental performance of one cluster branch depends on the performance of the other branches. For example, one branch's use of raw materials standards made by a cleaner technology in another cluster branch improves the environmental standards of the final product. Producing environmentally sound products is a prerequisite of market acceptance. However, doing so is not possible unless the whole cluster is involved.

Environmental impacts of different forest cluster branches vary considerably. The chemical forest industry comprises chemical pulping, mechanical pulping, recycled-fiber pulping, and papermaking. Different environmental issues are interlinked in the manufacturing processes. Improving environmental performance of any component has an immediate effect on the whole process. The printing industry is very different. The plants are usually much smaller. Compared with the huge integrates in the chemical wood-processing sector, the potential environmental damage caused by a single plant is minor. Environmental issues mainly concern inks and cleaning of the machines. Many improvements can be achieved in the printing sector with less influence on the process than in chemical wood processing.

One element common to both the chemical forest industry and the printing industry is the relatively high level of energy consumption. Electricity consumption by a sulfate pulp mill, a non-integrated fine paper mill, and a printing plant per ton of product are of the same size. The mechanical forest industry has good environmental standards. Raw material input to the industry consists mainly of logs that are processed efficiently with only a small amount of chemical aids. Energy and water consumption are considerably lower here than in chemical wood processing. In contrast, the wood furniture and wood preserving industries have a great impact on the environment because of the high amount of solvents used.

Figure 1.1 illustrates the forest cluster (Hernesniemi et al., 1996). Boxes with dashed lines are not included in this study. Emphasis is on the branches indicated with bold lines.

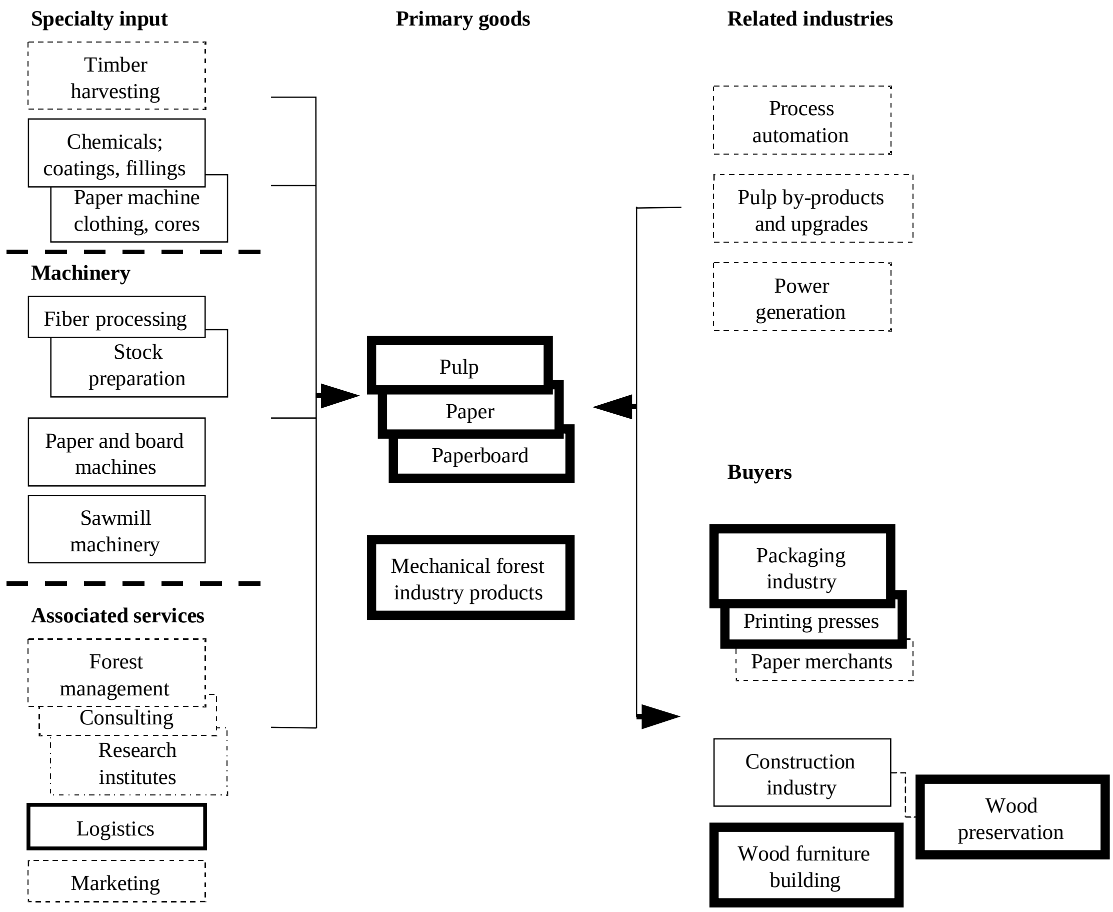

Figure 1.1. The forest cluster.

1.2 Objective and scope of the study

At the time of this writing, the preparation of a best available techniques (BAT) reference document for the pulp and paper industry is nearing completion.

Implementation of the Integrated Pollution Prevention Council (IPPC) directive requires the pulp and paper mills in the European Union (EU) to apply BAT. This report is not a substitute for the BAT document; its objective is to discuss environmental best practices for the entire forest cluster. In defining those best practices, I focus on how the manufacturing facilities of the forest clusters in the potential future EU member countries, which consist mainly of outdated plants, can be upgraded to meet current EU environmental standards. Cost issues and a comparison of different cluster branches are stressed. The concept "best practice" as defined is slightly different from best available technique.

The information presented in the study is based on numerous documents, environmental reports of forest cluster companies, expert opinions, and the literature in this field. This study concentrates on manufacturing processes. Some closely related operations, such as transportation and energy production, are briefly described. When analyzing environmental impacts of industries, the whole life cycle consisting of products, raw materials, and manufacturing facilities should be included. To narrow the scope, the life cycle analysis is excluded but life cycles are kept in mind.

Due to the different customer requirements, recycled-fiber-based paper and virgin-fiber-based paper, for example, are not compared from the environmental point of view. If the customer needs, which are currently fulfilled by virgin-fiber-based paper, could also be fulfilled by recycled-fiber-based paper, a comparison of those processes would be within the scope of this study.

Healthy, safety, and environment are often discussed in the same context. The first two subjects, however, are not within the scope of this study. Factors that mainly influence the environment of the working place or surrounding areas, such as noise and malodorous gases, are also excluded. Although it is a central component of the forest cluster, forestry is excluded. Some practices having an intermediate influence on forestry are described. The construction industry, except for wood preservation, is not within the scope of the study because of the large amount of products and production methods involved. Forming an overall picture would be a subject for another study. The packaging industry has a major impact on waste material generation. By modifying the packaging, huge environmental improvements could be achieved. Such a topic is too complicated to be included in this document.

1.3 Definitions

In preparing the IPPC directive and the best available technology (BAT) for the pulp and paper industry, Jaakko Pöyry Consulting used a triangle approach to describe the problems of definition (Vasara and Lobbas, 1999). *Figure 1.2* shows the two main triangles for defining environmental best practices.

In the triangles, the arrows show the direction of the axis of each factor; 1.0 denotes the best performance and 0.0, a worst performance. According to the triangles, best environmental performance can be achieved only by sacrificing cost and quality performances. This raises the question of what environmental best practice is. How much can environmental performance be required to improve at the expense of cost and quality?

The second triangle illustrates the interdependencies between different types of emissions. This triangle shows the difficulties in defining environmental performance. To define it exhaustively, it should be possible to define, for instance, whether a certain amount of discharged sulfur to air is a more disadvantageous emission than a certain amount of phosphorus discharged to water. Disadvantage coefficients for different emission types have been developed for monitoring emission reduction efforts (Metsä-Serla, 1998). An example of interdependence between different emission types is the current efforts to reduce water consumption in the pulp and paper industry. Naturally this reduces emissions to water, but in general it does so by generating more solid matter, which then must be disposed or recovered. One disposal method is incineration, but this generates air emissions. Another approach would be to accept the solid waste and then dipose of it in a landfill.

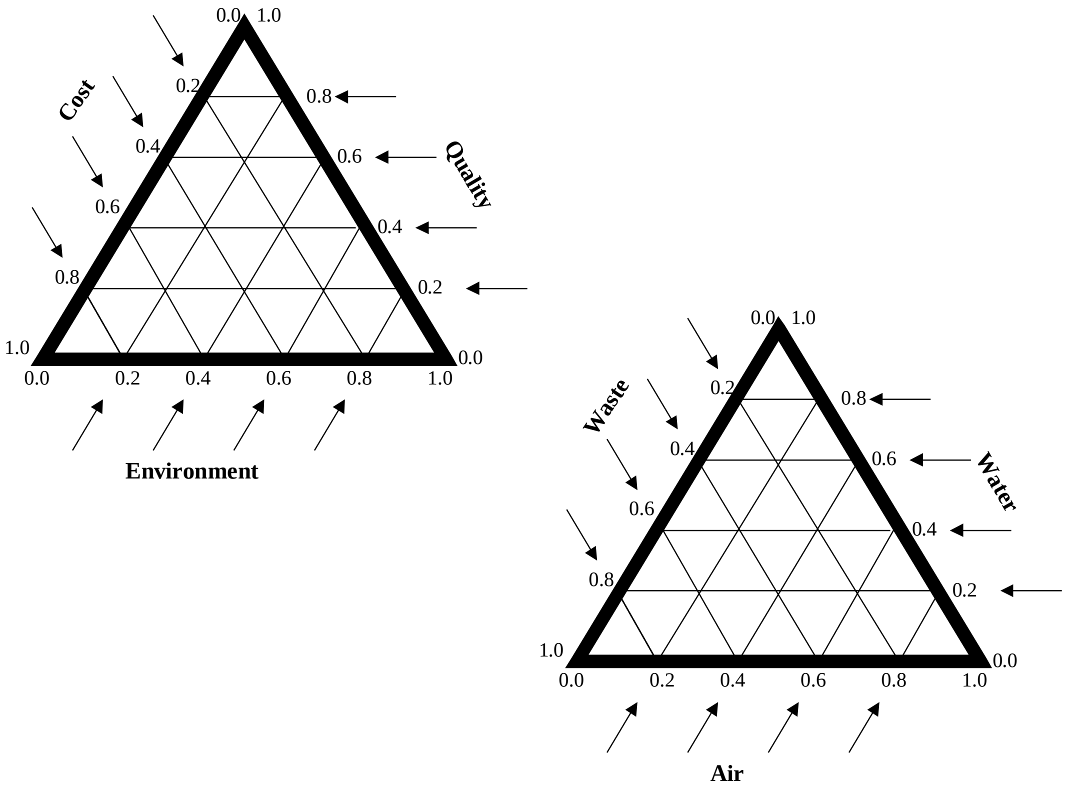

Figure 1.2. Main factors complicating the definition of environmental best practices.

Environmental reports from Finland’s pulp and paper industry since 1985 show that many companies have made efforts to meet the requirements within a short period of time. This has resulted in continual improvements and reinvestments in improved technologies. This is probably a much more expensive way to handle environmental issues than investing in the most efficient and modern technology in order to meet long-term requirements.

Differences in the environmental technologies used in different countries are not great. One of the most interesting differences between the major chemical pulp producers in Europe, Finland, and Sweden, is the external treatment of organic compounds. In 1997, only 4 of 10 bleached sulfate pulp mills in Sweden had a biological treatment plant (Södra, 1998). In Finland, all mills have a biological treament plant (Finnish Forest Industry Federation, 1991–1998). One explanation for this difference is the way development toward elemental chlorine-free pulp took place in the 1980s. Swedish mills adopted oxygen delignification and other internal methods to reduce the amount of lignin and, consequently, organic compounds in the pulp. At the same, time Finnish mills were building aerated lagoons, the most modern biological treatment method at that time. Finnish mills later implemented internal technologies, and emissions of biodegradable organic compounds are now much lower than in Swedish mills without external treatment.

Despite the difficulties presented above, two definitions of best available technology are given. The literature presents several explanations of environmental best practice. However, in this study, the definition is not straightforward in that it is the *combination of environmental best practices that most economically meets acceptable emission levels without sacrificing product quality.* Accordingly, a certain technique may be the best practice in one situation but not in another. A list of the best practices cannot be given in this document, but a discussion of the most promising techniques is provided. Although best management practices are as important as best available technology, they are excluded from this study.

The environmental efficiency of a practice is defined as emission reduction divided by the sum of incremental annual capital costs and operating costs.

2. Environmental impact of the EU's forest cluster

Figures 2.1–2.7 provide an overview of the environmental impact of different forest cluster branches in the EU. Wood products include sawn timber, plywood, particleboard, fiberboard, and preserved products. Printing includes all printing operations and packaging. Estimations are based on numerous sources. The real figures may therefore differ considerably from those presented below. The purpose here, however, is only to show the "big picture" in the cluster.

In the case of pulp and paper, sawn timber, plywood, particleboard, and fiberboard, production capacities used for some figures are based on the databases of the Food and Agriculture Organization (FAO). Emission estimations are based on numerous sources.[1] The production of forest cluster products is shown in *Table 2.1*. *Figures 2.1*, *2.2*, and *2.3* illustrate the sources of emissions to the air from the EU forest cluster.

Table 2.1. Production of forest cluster products in the EU.

Product	Capacity
Chemical pulp	20,764,000 tons
Recovered-fiber-based pulp	~ 25,000,000 tons
Mechanical and chemi-mechanical pulp	11,742,000 tons
Paper and paperboard	74,974,000 tons
Printing and packaging	< 70,000,000 tons
Sawn timber	71,425,000 m^3
Plywood	2,931,000 m^3
Particleboard	26,940,000 m^3
Fiberboard	4,570,000 m^3
Wood preservation	~ 6-10 Mm^3
Wood coating	~ 15,000,000 m^3

[1] The IIASA-RAINS database; environmental reports of various forest industry companies; figures of the US Environmental Protection Agency (1993); figures from the Finnish Forest Industry Federation; Luttmer, 1996; Bundesministerium für Umwelt, 1995; Ekono/Duoplan figures presented in the 1998 MoDo environmental report; *Atmospheric Emission Inventory Guidebook*, 1996; Koch, 1996; Klimont, 1997; Giddings et al., 1991; Silferberg et al., 1998.

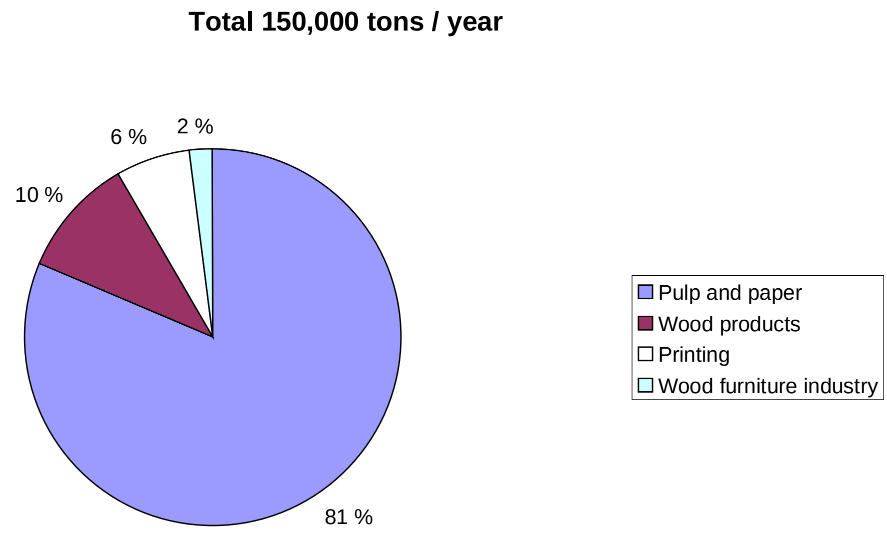

Figure 2.1. Estimated NO_x emission sources for EU forest cluster.

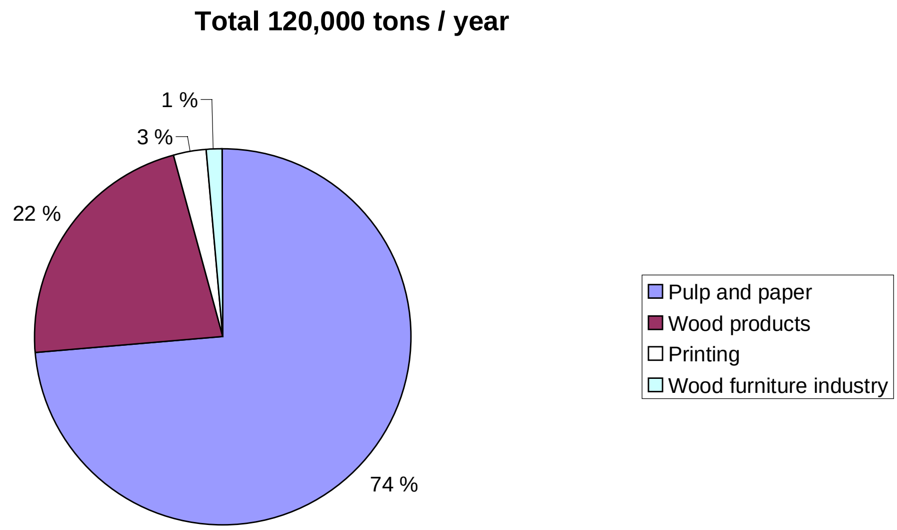

Figure 2.2. SO_2 emission sources for EU forest cluster (estimation).

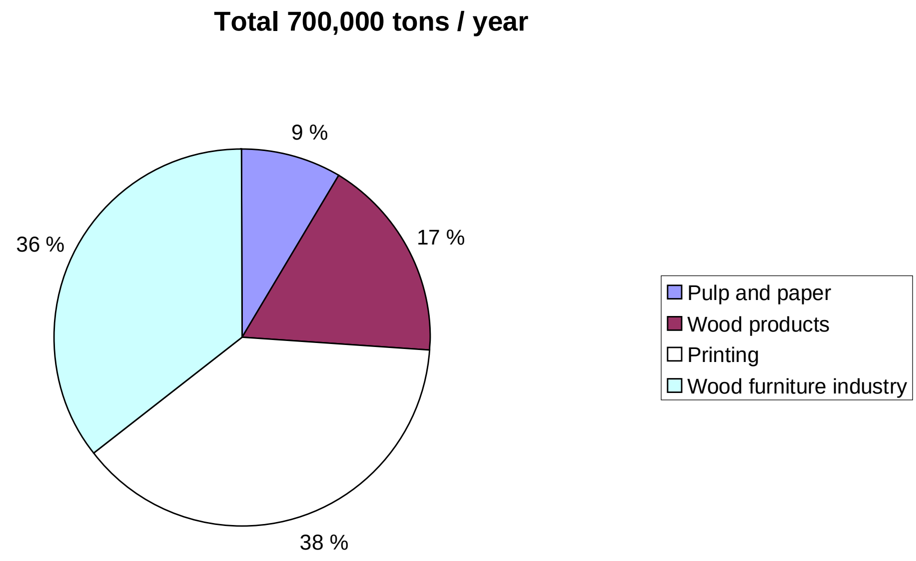

Figure 2.3. VOC emission sources for EU forest cluster (estimation).

The pulp and paper industry has the greatest environmental impact in the forest cluster. Only in the case of emissions of volatile organic compounds (VOCs) is the importance of the pulp and paper industry relatively small. However, VOC emissions from the forest cluster are approximately 6% of total VOC emissions in the EU, whereas emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) account for only around 1% of the total NO_x and SO_2 emissions in the EU. (Purchased energy has been excluded from this study.)

The printing industry produces considerably more NO_x emissions than SO_2 emissions. A probable reason is the use of NO_x-generating thermal afterburners for the destruction of VOCs. Environmental efforts to reduce SO_2 emissions from pulp production are evident in a comparison of the shares of the pulp and paper industry in total NO_x and SO_2 emissions. The relatively high proportion of wood products in the case of SO_2 can be largely explained by emissions from particleboard production. Wood furniture coating, printing, and wood preservation, which is included in wood products, generate the most VOC emissions.

Figure 2.4 illustrates the dominance of pulp and paper manufacturing as a source of chemical oxygen demand (COD) emissions to water. No estimates have been made for emissions to water from printing and wood furniture manufacturing. Nevertheless, it is obvious that pulp and paper is the principal source. A concern regarding the printing and wood furniture industries is emissions of hazardous compounds to water, including solvents, silver, and formaldehyde. These latter figures, however, are not available.

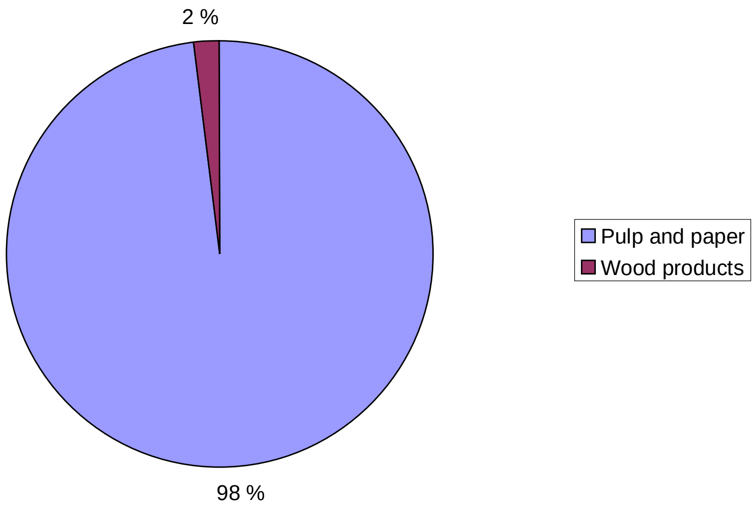

Figure 2.4. Estimated COD emission sources for EU forest cluster.

Figure 2.5 presents the electricity consumption of each cluster branch. Both purchased and electricity generated on site are included. This graph is also dominated by the pulp and paper industry, but the printing industry has quite large share, as well. In the case of wood furniture industry and fiberboard manufacturing, the same electricity consumption levels as in plywood production and particleboard manufacturing, respectively, are assumed. Energy efficiency is the best way to reduce carbon dioxide (CO_2) emissions.

Figure 2.6 illustrates emissions of particulate matter for the US forest cluster. Sources were not available for making a direct comparison for the EU forest cluster. The result would probably be quite similar because of the structural similarities between the forest clusters of the USA and the EU. Here, the importance of wood products and wood furniture building is greater than for NO_x and SO_2 emissions.

This paper concentrates on the manufacturing processes of the forest cluster. However, it is essential to include other emission sources, such as transportation. *Figure 2.7* presents an example of the importance of transportation with respect to emissions of NO_x to air.

The best practices for minimizing emissions in the local production chain may require a totally new structure of the forest cluster. Numerous examples support this idea. First, concerning transportation, from an ecological point of view it is better to convert products (e.g., coating and sheet cutting) as close to consumers as possible. Second, as an ecological solution, use of waste paper is currently preferred to use of virgin fiber. However, more transportation is required to recover paper than to supply timber. Even cleaner processes in the manufacture of chemical pulp may make virgin fiber preferable to recycled fiber from an environmental viewpoint. Analysis of the environmental impact of transportation in the forest cluster is beyond the scope of this study. However, it should be a part of future work in this area.

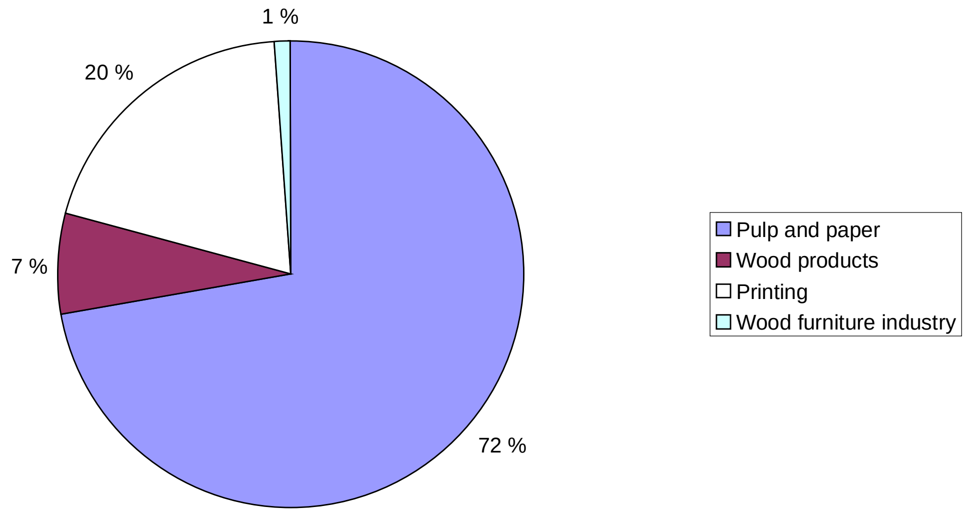

Figure 2.5. Estimated electricity consumption by EU forest cluster.

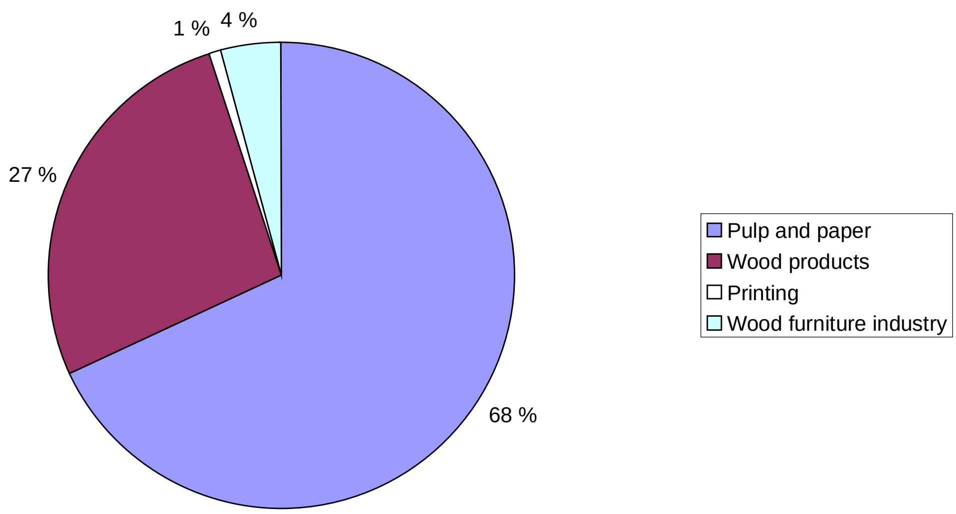

Figure 2.6. Particulate matter emission sources for US forest cluster.

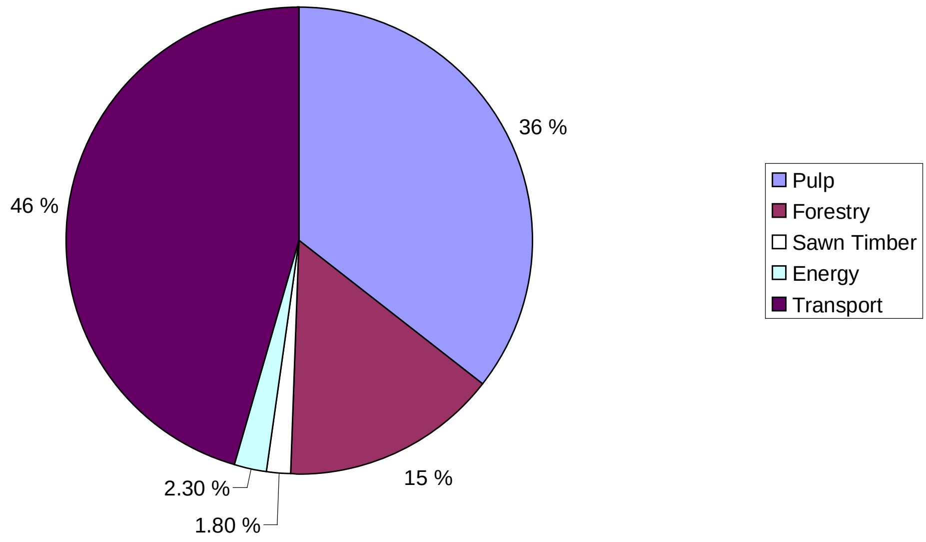

Figure 2.7. NO_x emission sources of a Swedish forest industry company.

3. Pulp

3.1 Chemical pulp

3.1.1 Chemical pulping and its environmental impact

In simple terms, chemical pulping means removing lignin from the wood substance using chemical treatment. This liberates the fibers from the wood matrix. There are two main processes: the sulfate or kraft process and the sulfite process. The sulfite process has been replaced by the kraft process in the most cases; for example, in Finland sulfite pulping is no longer used. The advantages of the kraft process are that different wood species can be used, the strength properties of the pulp are better, and recovery of chemicals is much more efficient than with the sulfite process. This paper deals only with kraft pulping, although in the EU's IPPC directive, both processes are discussed. As stated in the objectives of this study, excluding sulfite pulping can be justified in that both processes can be used to manufacture paper with similar functional properties, but the kraft process is more environmentally friendly.

Besides the almost complete abandonment of the sulfite process, several other radical changes have taken place in chemical pulping in the past two decades. First is the complete or parital replacement of elemental chlorine as a bleaching agent. In general, new greenfield mills produce only elemental chlorine free (ECF) or totally chlorine free (TCF) pulp. Second is the lowering of the water consumption level from around 100 m^3/t to almost 10 m^3/t in some mills. Levels of 10 m^3/t can be reached only with the TCF process. Third is the dramatic drop in emissions to both water and air. In the former case, the main reason is the more efficient external treatment of effluents, the elimination of elemental chlorine, and lower water consumption. In the latter case, according to experts in the field, the main factors are end-of-pipe technologies and higher dry-solids content of black liquor in the recovery boiler.

Figure 3.1 presents a simplified kraft pulping process. The two main parts of the process are fiber flow and the chemical production and recovery system. In the latter case, the system is rather complex and is not described in detail in this study. The most relevant process related to chemicals is the circulation of liquor.

The main stages of the fiber flow are debarking, chipping, cooking, washing and screening, oxygen delignification, second washing, bleaching, and drying. When manufacturing unbleached pulp, the bleaching stage is skipped.

Debarking is usually done in a debarking drum in which the friction between logs causes the debarking effect. Two processes are used: dry and wet debarking. Because of the much lower water consumption, dry debarking is recommended from both the environmental and the electricity-consumption points of view.

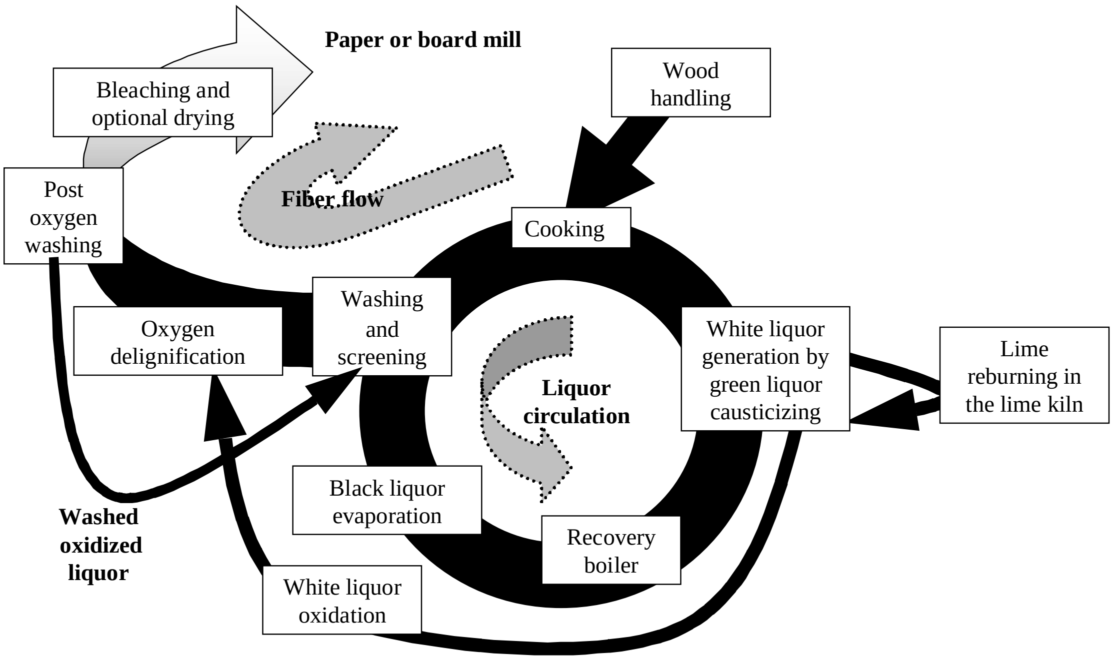

Figure 3.1. Fiber flow and main flows in circulation of chemicals at a kraft pulp mill.

It is crucial that the chipping and screening stages are performed properly. A uniform chip size is a prerequisite for a stable process and high-quality pulp. Rejected material is normally sent to the bark boiler (Ministry of the Environment, 1997).

Cooking is performed either in a continuous digester or in a batch digester. Continuous digesters are more common, but also batch digesters have recently been installed in modern mills. Chips are impregnated with white liquor and cooked at a high temperature to remove lignin. Several cooking modifications exist. They are discussed in the appendix to this report.

Used cooking liquor, or black liquor, which contains large amounts of lignin, is removed in the washing stage. Washing can be performed in a sequence of steps, resulting in increased lignin removal. Vacuum drum washers have traditionally been used, but in many cases other, more effective techniques have replaced such drum washers. Screening after washing increases the efficiency of the ensuing bleaching stage.

An optional stage before bleaching is oxygen delignification. In this phase, the amount of lignin is reduced further. This technology has been a step toward chlorine-free bleaching. The technique is described in the appendix. Oxygen delignification is not considered a part of the bleaching process because oxygen delignification takes place in the same water circulation system with the other unbleached pulp process.

Pulp is usually washed with fresh water after oxygen delignification (Ministry of the Environment, 1997). To prevent organic substances from being carried over through the bleaching plant to the effluent, the pulp should be as dry as possible before bleaching.

The cooking process cannot remove all lignin without remarkable yield loss. In the bleaching stage, a certain amount of the remaining lignin is removed, depending on the pulp brightness needs of the consumer. Chlorine is the most reactive bleaching chemical, but because of its generation of adsorbable organic halogens (AOX) and its contribution to corrosion, at many mills it has been replaced with other chemicals, including chlorine dioxide, peroxide, ozone, oxygen, and enzymes. Alkali, sodium hydroxide, is also used at the extraction stage. Chlorine dioxide is the most commonly used chemical. The disadvantage of both chlorine dioxide and ozone is that they have to be produced at the mill site and generators are expensive.

More than one chemical is needed due to their different reaction mechanisms. In general, chlorine dioxide, chlorine, ozone, or enzymes activate the fibers toward the lignin extraction stages, in which oxygen, peroxide, or alkali are used. The acid and alkali stages are alternated, and several repetitions are necessary. Peroxide reacts slowly with lignin, whereas ozone reacts quickly. The advantage of peroxide is that it brightens the remaining lignin.

Chlorine-dioxide-based ECF bleaching results in somewhat higher pulp strength and yield and lower chemical costs than ozone-based TCF bleaching (Ministry of the Environment, 1997). On the other hand, using chlorine dioxide does not eliminate the AOX concentration in the effluent. Chlorine dioxide produces approximately one-fourth the AOX produced by the same amount of elemental chlorine (Miller Freeman, 1991).

Effluents are usually treated using primary or mechanical treatment, secondary or biological treatment, and in some cases tertiary or chemical treatment. These are discussed in the appendix to this report.

In the liquor circulation flow, white liquor ($NaOH + Na_2S$) is used in cooking. As described above, black liquor is removed during the washing stage. After being concentrated and combusted in the recovery boiler, inorganic compounds are dissolved in water, generating green liquor. The recovery of valuable organic by-products such as tall oil is also carried out in the recovery boiler. Green liquor is further causticized, again forming white liquor. Lime mud is released in the causticizing process. It is washed and burned in the lime kiln, producing new lime for causticizing. The lime kiln is the only place in the kraft pulp mill where auxiliary fuel might be needed. Oxidized white liquor is also used in the oxygen delignification stage. In the last washing stage before bleaching, liquor components are separated and returned to the circulation flow.

According to the literature, several research papers, and consultant reports, the most important emissions from chemical wood processing can be categorized into the following groups. BAT ranges for non-integrated bleached kraft pulp mills are also given.

Water

- BOD (biological oxygen demand) describes the amount of biodegradable organic substances: 0.3–1.5 kg/air-dry ton (ADt).
- COD (chemical oxygen demand) describes the amount of all organic substances, including BOD: 10–15 kg/ADt.
- AOX (adsorbable organic halogens) is the amount of chlorine in the organic compounds: <0.05–0.2 kg/ADt.

- N (nitrogen) is a nutrient that contributes to eutrophication: 0.1–0.15 kg/ADt.
- P (phosphorus) is another nutrient that contributes to eutrophication: 0.01–0.02 kg/ADt.

Air
- SO_2 (sulfur dioxide): 0.3–0.8 kgS/ADt.
- TRS (total reduced sulfur): 0.1–0.3 kgS/ADt.
- NO_X (nitrogen oxides) : 1–2 kg/ADt.

Waste
- Nonhazardous waste to landfills: 30–60 kg/ADt.

VOC emission levels from pulping are difficult to ascertain. VOC emissions from Canadian kraft pulp processing were estimated to be 8.4 Ktons, accounting for 0.08% of produced air dry ton of pulp. Over 70% of the emissions are from recovery boiler stacks, blow tanks, and as digester release. In the case of the digester emissions, the gases are non-condensable and contain TRS, terpene, and methanol. TRS emissions consist of hydrogen sulfide and VOCs, with hydrogen sulfide predominating. If non-condensable gases are collected and burned, VOC emissions are significantly lower. Compared with other industries, SO_2, NO_x, and especially particulate emissions from the pulp industry are considerably higher than VOC emissions (*Atmospheric Emission Inventory Guidebook,* 1996).

For kraft pulping, emissions to water are the greatest concern (Ministry of the Environment, 1997). Emissions to water originate from wood handling, washing, condensates, spills, and bleach plant effluents. In many cases, wood handling and bleaching are the only permanent sources of emissions. Condensates form in the cooking and black liquor evaporation stages. Nitrogen emissions are mainly generated in the unbleached pulp side and phosphorous, on the bleached pulp side (Nordic Council of Ministers, 1993).

NO_x, SO_2, and TRS emissions to the air originate from the different boilers and the lime kiln. Malodorous gases, consisting mainly of the TRS that forms during the cooking, washing, and evaporation stages, can be collected and burned in the lime kiln or in a dedicated incinerator.

Solid waste consists of inorganic sludge from chemical recovery, dust, residues from wood handling, and ashes and sludge from effluent treatment. Combustion and landfills are the standard removal methods (Swedish Environmental Protection Agency, 1997).

Bleaching plants are the primary source of emissions to water even if emissions caused by other processes had been subtracted from the emission levels of bleach plant effluents. For example, so-called washing loss, or the organic substances that are not removed due to incomplete washing, is carried over to the bleach plant effluent. In the case of emissions to the air, around 40% of sulfur emissions emanate from the pulping process, the rest are from energy production. At some mills SO_2 is dominant, at other mills TRS predominates. In the case of NO_x, one-third of the emissions are from the pulping process; the rest are from energy production (Saarinen et al., 1998).

A modern pulp mill is more than self-sufficient with respect to energy. The surplus of heat is 1.5–2 MWh/ton, and that of electricity is 500 kWh/ton. Over 50% of the electrical energy consumption of around 800 kWh/ton is used for pumping and 15–20% is used for drying.

Lower water consumption results in lower energy consumption for achieving the required process temperature and for pumping (Ministry of the Environment, 1997). If a pulp mill is integrated with a paper mill, the pulp is not dried after bleaching. The energy savings are approximately 1MWh/ton (Lahti-Nuuttila, 1998).

In general, the highest daily emissions usually occur when production is stopped or started. Production is stopped during extensive maintenance operations, and if the recovery boiler or the evaporation plant become obstructed. According to experts in the field, progressive monitoring methods are important in preventing these occasions.

3.1.2 Best practices in chemical pulping

The practices discussed in this section are presented in the appendix.

In this study, kraft pulping is the only industry in which environmental best practices can be analyzed using reliable data concerning emissions, investment costs, and operating costs. However, because of cross-media effects, calculating the environmental efficiency with respect to only one emission type may be misleading. Furthermore, the investment costs and emission reductions listed in different reports are only average values and are highly dependent on the mill site. For example, building a biological treatment plant is more attractive when the wastewater of a nearby city can be led to the same treatment plant and hence the city also funds the project. Investment costs for different mills can vary considerably. Costs are dependent on compatibility with previous investments.

The pulp and paper industry is currently undergoing a major change as a result of ownership changes and increased dominance of shareholders. The investment decision process now undergoes more detailed investigations than it previously did. One consideration is the investment strategy — whether to maintain and renew the original investment for decades or to use a production line until its natural "death" without major revisions and huge maintenance costs. According to experts, Europeans have traditionally followed the first strategy and Americans, the latter.

This study should give some background for upgrading the mills in Eastern Europe. Many of the mills there are in very bad shape, and both strategies — renewing the mills and building completely or almost completely new mills — should be considered.

Figures 3.2, *3.3*, and *3.4* present the environmental efficiencies of different techniques. The techniques with the highest environmental efficiencies should be considered first when upgrading the environmental performance of a mill. The data are mostly based on JRC (1998), Swedish Environmental Protection Agency (1997), and US EPA (1993). A mill capacity of around 300,000 t/year is assumed. The term incremental annual costs refers to the sum of incremental annual capital costs and operating costs. The interest rate is not included. The analysis cannot be used at the mill level; however, the large differences between different technologies can be shown.

Figure 3.2 illustrates environmental efficiencies of some techniques with respect to COD emissions. Although COD may not be the most important emission type in every case, it is the most commonly presented and therefore extensive information on it is available.

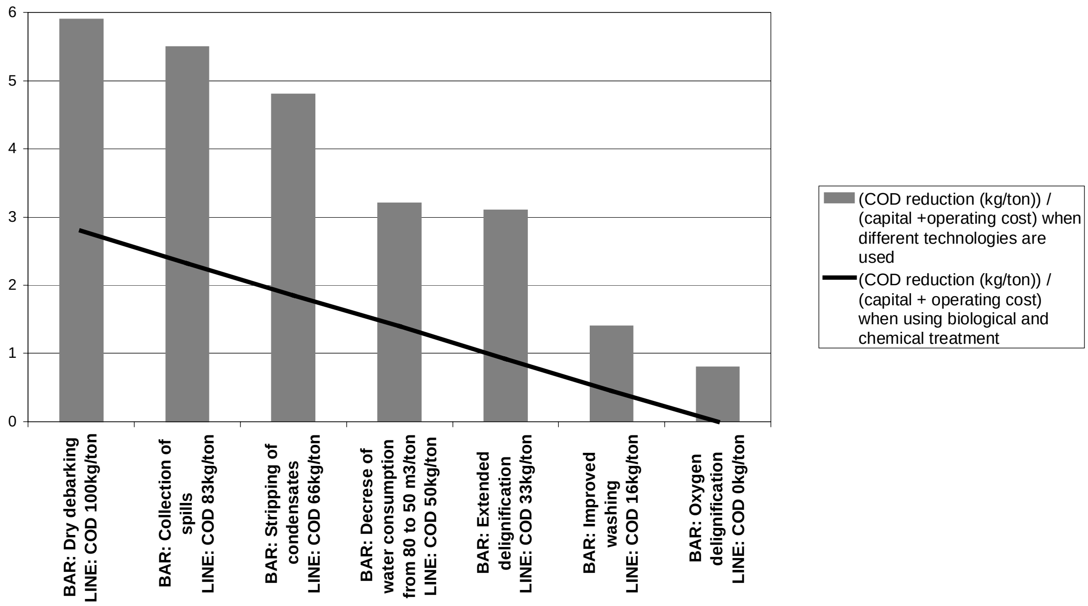

Figure 3.2. COD emission reduction efficiency of different technologies in bleached kraft pulp mills.

The investment costs of dry debarking are quite low if the existing drum is long enough, as is assumed here. With short drums, the cost is higher and, consequently, the environmental efficiency is much lower. The environmental benefit of 20 kg/air-dry ton (ADt), measured as COD, and an incremental cost of 0.38 million ECU are used. No major cross-media effects exist.

An improved spill collection system does not necessarily require large investments. The cost is dependent on the changes required in the layout of a mill. An environmental benefit of 5.5 kg/ADt, measured as COD, and an incremental cost of 0.11 million ECU are used. In other words, it is assumed that there is no need to expand evaporation capacity.

Stripping of condensates can be carried out in a separate stripper or can be integrated into an evaporation plant. An environmental benefit of 21 kg/ADt, measured as COD, and an incremental cost of 0.49 million ECU are used.

Recovering alkaline filtrate in a bleach plant and partially shutting down the bleach plant is one way to reduce COD and BOD emissions. An environmental benefit of 8 kg/ADt, measured as COD, and an incremental cost of 0.28 million ECU are used. These figures are, however, the most uncertain of the estimates presented. Potential COD emissions from a bleach plant depend on the COD level of the pulp entering the plant.

Extended delignification is used to reduce the amount of elemental chlorine used. Many types of extended delignification exist and investment costs vary considerably (US EPA, 1993). An environmental benefit of 25 kg/ADt, measured as COD, and an incremental cost of 0.90 million ECU are used. This benefit can be achieved when coniferous wood is processed. In the case of non-coniferous wood, the efficiency of extended cooking is much lower, but the yield in cooking is higher. Both negative and positive cross-media effects exist.

The cost of improving the washing sequence and potential COD and BOD reductions depends on the existing washing equipment. An environmental benefit of 3 kg/ADt, measured as COD, and an incremental cost of 0.28 million ECU are used, corresponding to the replacement of very old washing equipment with modern equipment.

Introducing oxygen delignification is one step toward ECF or TCF bleaching. The technique itself has quite low environmental efficiency. An environmental benefit of 25 kg/ADt, measured as COD, and an incremental cost of 3.57 million ECU are used.

The environmental efficiency of an external treatment plant depends on the load of pollutant to be disposed of. If, for example, no internal environmental improvements have been carried out and COD before external treatment is high, the environmental efficiency of the external treatment plant is high. The figure presented is the investment cost of modern combined activated sludge treatment and chemical precipitation. An incremental cost of 3.34 million ECU and a COD reduction capability of 85% are assumed.

Achieving the highest possible reduction rates in external treatment requires good knowledge of how the plant operates. Nutrient concentration, for example, should be at exactly the right level. Monitoring systems and automatic dosing systems are available, but they increase the investment cost of a plant.

High fluctuations in emission figures, even where the technologies applied are quite similar, show that monitoring, management, and maintenance have a great influence on environmental performance (Finnish Forest Industry Federation, 1991–1998). Therefore, introducing the concept of environmental efficiency can be useful. A pitfall in focusing too closely on economical efficiency of single technologies is that the production line as a whole is not taken into account. For example, even after installing the most efficient internal environmental technologies, a mill may still need external treatment in order to achieve emission requirements. On the other hand, implementing only the external treatment might have been enough to achieve those requirements.

Investments in external treatment are especially attractive at mills with old machines. There, the expected lifetime of a production line plays a central role: when it is low, annual capital costs can be unacceptably high. However, the external treatment facilities can be still used if a new production line is built at the site or if total revision is carried out.

Figures 3.3 and *3.4* illustrate the environmental efficiencies of some techniques with respect to emissions to the air at a kraft pulp mill. Because of a lack of information with respect to particulate matter and VOC emissions, only NO_X and SO_2 are discussed here.

In the case of NO_X emissions, the most efficient way for improvements is to use low-NO_X technology in auxiliary boilers. An environmental benefit of 31 units/ADt and an incremental cost of 0.07 million ECU are used. The auxiliary boiler is assumed to be a bark boiler. Units are based on the estimation that NO_X emissions from a bark boiler are twice those from a recovery boiler per energy unit and the energy production from a recovery boiler is five times that from a bark boiler. The characteristic discharge of NO_x is approximately 50 mg/MJ from a recovery boiler, 100 mg/MJ from a bark boiler, and 450 mg/MJ from a coal boiler (Lammi, 1997). The environmental efficiencies of changing urea to the recovery or bark boiler for NO_X reduction are quite similar.

In the case of changing the air inlet, an environmental benefit of 30 units/ADt and an incremental cost of 0.17 million ECU are used. In the case of the SNCR to the bark boiler, an environmental benefit of 20 units/ADt and an incremental cost of 0.12 million ECU are used. Finally, in the case of adding SNCR to the recovery boiler, an environmental benefit of 60 units/ADt and an incremental cost of 0.41 million ECU are used.

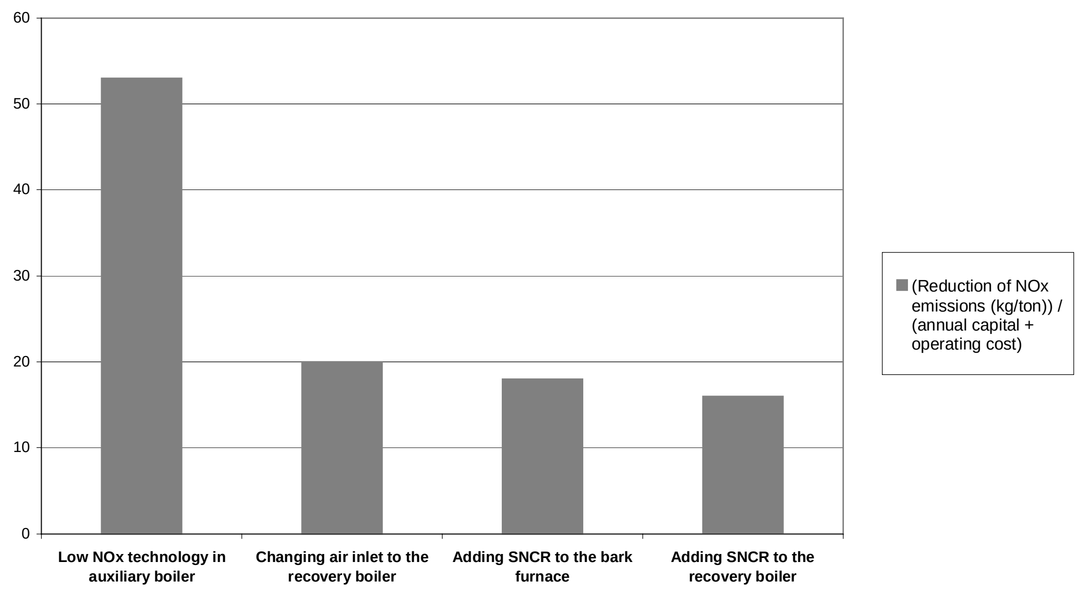

Figure 3.3. NO_x emission reduction efficiency of different technologies at a bleached or unbleached kraft pulp mill.

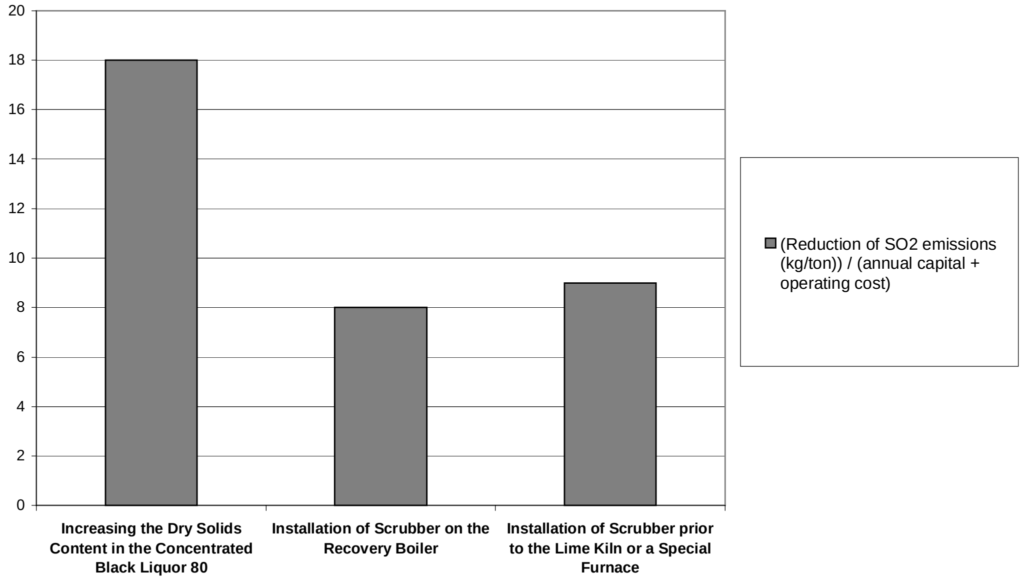

Figure 3.4. SO_2 emission reduction efficiency of different technologies at a bleached or unbleached kraft pulp mill.

Increasing the dry solids content in the black liquor is the most efficient way to reduce SO_2 emissions. The resulting emission reduction performance is similar to that of a scrubber, but the sum of capital costs and annual operating costs is about half that of a scrubber. When the evaporation capacity is a bottleneck, the situation can be different. The economic efficiency of a scrubber for a lime kiln is approximately as high as that for a recovery boiler if non-condensable gases are burned in the lime kiln. Otherwise the scrubber is not needed.

In the case of increasing the dry solids content, an environmental benefit of 80 units/ADt and an incremental cost of 0.50 million ECU are used. Units are based on the assumption that the characteristic emission, without end-of-pipe technologies, from a lime kiln is 14% of that of a recovery boiler (JRC, 1998). In the case of a scrubber for the recovery boiler, an environmental benefit of 90 units/ADt and an incremental cost of 1.25 million ECU are used. Finally, in the case of a scrubber for the lime kiln, an environmental benefit of 13 units/ADt and an incremental cost of 0.16 million ECU are used. Improved washing of lime mud is not discussed in this context. Reduction rates for sulfur are not available. It is, however, obvious that the environmental efficiency of lime mud washing is lower than the efficiencies of the techniques presented above.

In the following example, two strategies are presented for an old kraft pulp mill without any internal environmental technologies, with limited chlorine dioxide (ClO_2) production capacity, and mechanical treatment and an aerated lagoon for biological treatment of effluents. Both strategies fulfill the emissions requirements (JRC, 1998). Strategy B results in better environmental performance. Strategy A leaves open the option of future investments in a new pulp line while retaining the same kind of wood handling and external treatment. A kraft pulp mill has a BOD discharge of about 25 kg/ton, a COD discharge of 90 kg/ton, and an AOX discharge of 8 kg/ton before external treatment. In the case of unbleached pulp, BOD is 15 kg/ton and COD is 50 kg/ton (Swedish Environmental Protection Agency, 1997). The cost estimates and emission reductions used in the following examples are based on several sources (Swedish Environmental Protection Agency, 1997; JRC, 1998; US EPA, 1993; Södra, 1998).

Strategy A

By replacing the old lagoon with combined extended aerated activated sludge treatment and chemical precipitation, the emissions can be reduced to 10–15 kg/ton of COD, 2–3 kg/ton of BOD, and 1.5 kg/ton of AOX (see *Table 3.1*). The incremental annual cost for a 10-year lifetime is around 1.9 million ECU (Södra, 1998). Generally speaking, the levels of BOD and AOX are not at the required levels. In this situation, the AOX level can be reduced to an acceptable level only through ECF or TCF bleaching or high ClO_2 substitution with best available chemical treatment. There is an optional substitution level. When decreasing elemental chlorine consumption, ClO_2 must be increased exponentially (Miller Freeman, 1991). The most economic way to reduce AOX levels before external treatment is to expand ClO_2 capacity and adopt a peroxide extraction stage. Using any other bleaching chemical is expensive compared with using chlorine (Kisser and Kirschten, 1996). The investment costs are very site specific and contradictory estimations exist. The annual incremental cost is around 2.1 million ECU and the total annual cost after this measure 4.0 million ECU. The BOD level can be reduced most efficiently by introducing dry debarking. If the existing drum is long enough, the annual retrofitting cost is 0.5 million ECU. Thereafter, the total cost is 4.5 million ECU.

Strategy B

In this strategy, the internal process of the production line is improved. Dry debarking, extended cooking, improved washing, more effective collection of spills, stripping of condensates, and ECF bleaching are introduced, resulting in an annual cost of 7.7 million ECU. The ECF bleaching section is the most expensive part of the investment. The mill continues to use the same aerated lagoon. In principle, an effective lagoon is enough if internal performance is at a high level, as has been shown, for instance, by two StoraEnso mills in Finland (Finnish Forest Industry Federation, 1991–1998).

Comparing the costs of the two strategies shows that strategy A is less expensive if the goal is limited to meeting the required emission levels. In general, such a strategy will not lead the pulp mills of Eastern Europe in a more environmentally sound direction. However, the example shows that more than one option is available. Strategy A is a good alternative where funding for building a totally new production line is not available but a new line is planned for the future. If consumers require pulp to be ECF or TCF bleached, strategy B is the only possibility.

In the case of unbleached pulp, the required environmental performance can be achieved through internal measures and external treatment. The annual cost of the internal measures is the cost of strategy A minus the cost of bleaching revision, totaling 2.4 million ECU based on a 10-year lifetime for the investment. The annual cost of the external treatment is around 3.5 million ECU.

In addition to the possible best practices presented above, there are a few other techniques with high environmental efficiency. For instance, separating cooling waters from the other waters decreases freshwater consumption. Introducing an emergency basin in the external treatment process reduces the amount of discharged BOD and COD. Finally, incineration of concentrated TRS gases can be carried out. The investments required for these measures are relatively small (Confederation of European Paper Industries, 1997). One important application in the field of biotechnical carbon hydrate research on wood is enzyme bleaching of the pulp. The use of chlorine chemicals can be reduced with very little investment (KTM, 1994).

Environmental best practices are quite similar when refitting an existing mill or when building a completely new line. However, the example above shows that even at the same mill practices may differ depending on the strategies for the future chosen. In the case of an existing mill, one considerable restriction for renewal is the capacity utilization rate. If there is no extra capacity in the recovery boiler or the evaporation stage, there are few economically attractive alternatives for improving environmental performance.

Table 3.1. Costs for reducing emissions to water in an old-fashioned kraft pulp mill with an aerated lagoon as an external treatment method. Lifetime of 10 years, interest rate not included.

Strategy A	**Annual cost (million ECU)**	**Strategy B**	**Annual cost (million ECU)**
Extended aerated activated sludge treatment + chemical precipitation	1.9	Extended cooking	0.9
Dry debarking	0.5	Dry debarking	0.5
50% elemental chlorine substitution for chlorine dioxide	2.1	ECF bleaching	5.5
		More effective collection of spills	0.1
		Stripping of condensates	0.5
		Improved washing	0.2
Total	4.5	Total	7.7
Result	Required	Result	Better than required

At an existing mill, radical closure is out of the question. If measures to reduce water consumption are planned, improvements in the chemical recovery system are required. Evaporation and recovery boiler capacities often are bottlenecks in existing mills. Increasing capacity is very expensive compared with the difference between the cost of a low-capacity boiler or evaporator and a high-capacity boiler or evaporator when planning a new mill. Unfortunately, increased evaporation needs usually mean that a new evaporation plant has to be installed (Swedish Environmental Protection Agency, 1997). In the early 1990s, the US Environmental Protection Agency listed some options for increasing chemical recovery capacity at existing mills. Alternatives include building an extra evaporator, transporting black liquor to another facility, lowering the heat value of black liquor using oxidation, separating the soap from the black liquor, and increasing black liquor storage capacity (US EPA, 1993). One alternative is to increase the dry solids content of the black liquor, but in that case more evaporation capacity is required.

With regard to spill control improvements, layout changes required for a spill collection system can be extremely costly at existing mills. Monitoring systems for spills, however, are relatively easy to install (US EPA, 1993).

Other techniques that are not economically very attractive at existing mills include installation of an electrostatic precipitator for particulate matter emission reduction, handling of TRS gases, and separation of cooling waters (Confederation of European Paper Industries, 1997).

The energy production rate of the recovery boiler is proportional to the pressure used in combustion. In principle, there are no obstacles to a considerable increase in pressure. However, increased pressure tends to raise the probability of a boiler explosion. The latest control and monitoring systems could enable an increase of pressure. Higher energy production would reduce the consumption of fossil fuels and thus reduce emissions of CO_2, NO_X, and SO_2.

Sludge from external treatment can serve as a fuel. If it is dried enough and mixed with other wood waste, sludge can partially replace fossil fuels and thus reduce CO_2 emissions. The cost of a screw press for drying the sludge is around 0.5 million ECU (Enso, 1997a, 1997b). Information on cross-media effects from using it is not readily available.

3.1.3 Possible future

Pressurized black liquor gasification is mentioned as a potential way to increase the electricity production of a recovery boiler from the present level of around 800 kWh/ton up to 1,500 or 2,000 kWh/ton (Renberg and Axegard, 1998). It can also increase a recovery boiler’s capacity for treating recovered chemicals. The technique is still far from being commonly adopted (JRC, 1998).

In the future, mills may be potassium based instead of sodium based. There are several advantages to such a change. The natural potassium content of wood is much higher than the sodium content. Potassium is currently a undesirable substance in the pulping process. In a potassium-based system, it would be the sodium that would be unwelcome. Its concentration, however, would be much lower than the concentration of potassium in the current process. In a potassium-based system, a much larger part of the alkali could be taken out as a useful resource. For instance, potassium chloride is a commercially viable product. All alkali and sulfur acid needed could be generated from potassium sulfate, and the bleach plant would be truly integrated. One problem in changing from a sodium-based system to a potassium-based system lies in creating a process corresponding to the causticizing in the present system (Renberg and Axegard,1998).

The so-called organosolve method in pulp making has been the subject of research for many years. One plant using this method went into operation in Germany but was later closed. In the organosolve method, cooking chemicals are replaced by organic acids and solvents. The greatest problem is in the recovery of the solvents (KTM, 1994; Nordic Council of Ministers, 1993).

3.2 Mechanical pulp

3.2.1 Mechanical pulping and its environmental impact

With few exceptions, mechanical pulp mills are integrated with paper mills. This has both positive and negative effects on the environment (see discussion in Section 4.4). Emissions from mechanical pulp mills are lower than emissions from kraft pulp mills, mainly because of the high yield in mechanical pulp production. There are three main categories of mechanical pulp: groundwood pulp, refining pulp, and chemi-mechanical pulp. *Figure 3.5* shows the steps in the two first categories. In both the grinding and refining processes, the temperature is increased to soften the lignin. This breaks the bonds between the fibers.

If timber for mechanical pulping is stored, the wood should not be allowed to dry out. Water and a water collection systems are needed. Wood is used as logs in groundwood pulping and as chips in refining pulping. Chips are washed to remove undesired particles before refining, resulting in effluent.

In the stone groundwood (SGW) process, logs are pressed toward a grinding stone. Water is used as a coolant and a transport medium for the pulp (Nordic Council of Ministers, 1993). By increasing the pressure, a higher temperature can be used, resulting in softer wood and less-damaged fibers.

In the refiner mechanical pulping, chips are ground between steel disks in a refiner (Ministry of the Environment, 1997). Again, an increased temperature results in less damaged fibers in this process. In the thermo-mechanical process (TMP), the first step is a heat pretreatment of the wood chips under pressure and then pressurized refining. Two refining steps are usually used in TMP (Swedish Environmental Protection Agency, 1997). In the chemi-thermo-mechanical process (CTMP), TMP is combined with a mild chemical treatment before pressurized refining (Nordic Council of Ministers, 1993).

A significant amount of the heat generated in mechanical pulping is converted to low-pressure steam used to dry paper. However, the energy recovery potential of mechanical pulping is moderate compared with that of chemical pulping. The energy recovered in TMP is 1,000–1,500 kWh/ton, representing 30–40% of the total energy consumption in TMP (Ministry of the Environment, 1997).

The stage after mechanical pulping is screening. Pressurized screens with slotted plates have replaced hydrocyclones in many applications. Energy consumption has decreased. Centrifugal separation is used as a supplement to pressurized screening (Confederation of European Paper Industries, 1997; JRC, 1998). The objective is to return the rejects to the fiber system after treatment. This is not done in chemical pulping. Washing and screening generate final rejects of 1.5% of the amount of pulp (JRC, 1998). From an environmental point of view, it is not clear that a smaller amount of final reject is preferable. Refining and returning rejects to the fiber system requires energy. Moreover, accepting bad-quality fiber may result in disturbances in the process.

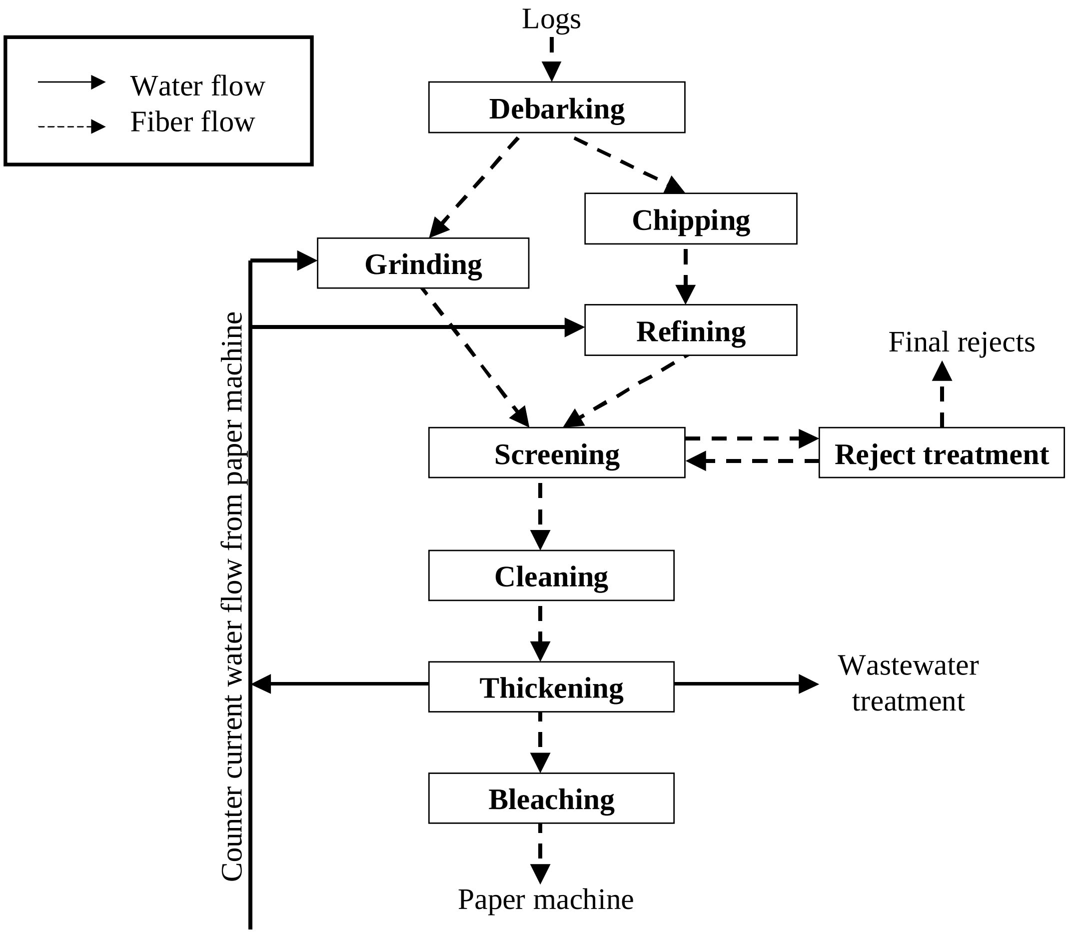

Figure 3.5. Mechanical pulping.

Cleaning and thickening with disk filters after screening removes large portions of water carrying BOD and COD. Part of the water flows counter to the pulp flow to the grinding or refining stages. Part of the water is directed to external treatment to keep the concentration of unwelcome substances in the water low.

Bleaching of mechanical pulps is performed by using dithionite or hydrogen peroxide. In contrast to chemical pulp bleaching, the bleaching of mechanical pulps aims at changing the chromophoric groups in the lignin into a colorless form, not at removing lignin (Ministry of the Environment, 1997). In bleaching, a chelating agent such as EDTA increases the nitrogen emissions to water (JRC, 1998). Peroxide bleaching causes a 2% yield drop. This bleaching improves the strength of the pulp; however, the yield loss increases COD and BOD emissions considerably.

Required emission levels from TMP mills are as follows:

Water
- BOD: 0.3–0.7 kg/ADt
- COD: 3–7 kg/ADt
- AOX: 0 kg/ADt
- N: 0.04–0.1 kg/ADt
- P: 0.004–0.01 kg/ADt

Air
- SO_2: 0.02–0.03 kgS/ADt
- TRS: 0.1–0.3 kgS/ADt
- NO_X : 0.2–0.3 kg/ADt

Waste
- Nonhazardous waste to landfills: 40–50 kg/ADt (JRC, 1998)

These are site-specific levels excluding purchased electricity, which accounts for over half the consumption. The differences in emission levels between different mechanical pulp processing technologies are not dramatic.

The environmental impact of mechanical pulping depends strongly on customer requirements. The strength of the pulp is negatively correlated with the yield and consequently with emissions to water and energy consumption. As mentioned above, the same is true concerning brightness requirements. Approximate coefficients of yield reduction with respect to emissions to water are as follows:

- Yield reduction in percentage times 3.5 roughly corresponds to the increase of emissions of BOD in kg/ton
- Yield reduction in percentage times 15 roughly corresponds to the increase of emissions of COD in kg/ton (Ministry of the Environment, 1997; JRC, 1998)

Effluent flows from mechanical pulp mills are small compared with those of chemical pulp mills; flows as low as 2–4 m^3/ton can be achieved. The effluent volume from a

CTMP mill is 7–10 m^3/ton. The trend is toward lower water usage. Freezing, evaporation, and filtration are among the internal measures to reuse water.

Emissions to the air are modest in mechanical pulping. Production emissions of purchased electricity can be high (Nordic Council of Ministers, 1993).

3.2.2 Best practices in mechanical pulping

Because of limited data availability and the characteristics of the process, it is not possible to use the same kind of approach as presented for chemical pulping to evaluate the best practices in mechanical pulping. Some examples are given in this section, but mechanical pulping is also discussed to some extent in the section describing papermaking.

Work is being done on refining technologies to decrease energy consumption and increase the content of fines to improve the opacity of paper. Electricity consumption is very high, especially in TMP production for magazine papers, even reaching 3MWh/t. Energy consumption can be reduced 10–20% through two-disk refining, higher refining frequency, and refining of only selected fibers using fractionating. The techniques, however, may lower the strength of the pulp. It is also possible to remove fibers and fines in several steps during refining and to refine only the fibers that need it. This reduces energy consumption. If opacity is not critical, chemical treatment before refining can improve the tensile strength. The mechanical pulping process is largely an optimizing process where the variables are strength, opacity, and bulk (Sundholm, 1996).

In dithionite bleaching there is no need for a separate bleaching tower. Consequently, the investment costs are very low. Moreover, compared with peroxide bleaching, the operating costs are much lower (Swedish Environmental Protection Agency, 1997).

When comparing existing and new mills, some differences in environmental efficiency have to be taken into account. Separation of cooling waters from other waters at the existing mill can be very costly because of required layout changes. Internal measures to recirculate more process water and recover more fibers can be expensive. In contrast, the cost of a primary clarifier is low at both existing and new mills. A primary clarifier is very effective in reducing total suspended solids (TSS) in external treatment (Confederation of European Paper Industries, 1997).

Improving washing efficiency in CTMP manufacturing decreases the carryover of organic compounds to paper or board mill. Drum washers, twin wire presses or screw presses are used (JRC, 1998).

CTMP processing, including chemical treatment, generates more solids separated from wood. Using evaporation in external treatment is economically more attractive than at mechanical pulp mills. The concentrate can be burned or evaporation can be used for the most contaminated wastewater.

Internal chemical treatment can be used to reduce COD (JRC, 1998). Internal clarification of circulation water through flotation can lower water consumption at TMP mills (Swedish Environmental Protection Agency, 1997).

The purpose of incineration — that is, whether electricity or heat is wanted — is an important factor concerning emissions to the air. High-pressure steam for electricity production requires support fuel when different wood rejects are burned. Calcium can be used in a boiler for binding sulfur (JRC, 1998).

In a combined heat power plant (CHP), a steam boiler and turbo-generator follow the gas turbine generator. The share of electrical energy is increased, which is preferable in mechanical pulping. The efficiency of a CHP plant is very high. If only electricity is produced, the efficiency is 60% (Lahti-Nuuttila, 1998). Thermal efficiency is 90%, compared with only around 40% in a normal energy plant. This reduces CO_2 emissions considerably (JRC, 1998).

Research has been conducted on enzyme pretreatment before mechanical treatment. Energy savings can be considerable, reaching up to 15–20% (KTM, 1994).

External treatment methods are generally the same as in chemical pulping. However, anaerobic treatment is more suitable for a CTMP mill than for a chemical pulp mill. The main reasons are higher BOD concentration and the absence of compounds that disturb the process (Miller Freeman, 1991).

3.3 Recycled fiber pulp

3.3.1 Recycled-fiber pulping and its environmental impact

Recycled-fiber pulping has many characteristics that set it apart from virgin fiber pulping. Using recycled fiber as a raw material is considered to be more environmentally friendly. The production process emissions are lower and recycling reduces both the amount of waste paper sent to landfills and wood harvestings demands. An often neglected characteristic is transportation emissions. Collecting waste paper and using small sites in its processing may lead to substantial transportation needs, assuming that waste paper is collected separately from other municipal waste. Taking this into account, using recycled fiber can cause greater environmental impacts than the most modern chemical pulping technologies (Weaver et al., 1997). Another special characteristic of recycled fiber processing is its dependency on the virgin fiber pulping, papermaking, printing, and packaging processes used: the chemicals that are used have an influence on recyclability of paper.

Emissions from recycled-fiber-based pulp mills are strongly dependent on the needs of the end user. The main stages are

- Coarse classification
- Re-pulping
- Removal of mechanical impurities
- Deinking by flotation or washing or both
- Mechanical or chemical dispersion of remaining contaminants
- Dewatering
- Bleaching (Ministry of the Environment, 1997)

Deinking is needed for certain grades of paper such as magazine papers, newspaper, and tissue. Flotation is used to remove larger particles and washing is used to remove smaller particles. Ink pigments, for instance, are removed mainly by flotation. Washing can be characterized as multistage dewatering. Both flotation and washing are required, for example, deinking magazine paper (JRC, 1998).

Bleaching of recycled-fiber-based pulp is performed using the same chemicals as are used in mechanical pulping. To a large extent, the environmental issues concerned are the same.

The amount of residues and rejects from different impurity removal stages is highly dependent on the grade produced. It can vary between 5% and 20% of waste paper processed and can go even higher for grades, such as tissue (Luttmer, 1996).

Rejects constitute 6.5% of the purchased waste paper and have no recycling potential because they contain impurities such as plastic. Rejects are dewatered using drums and screw presses (JRC, 1998). Because of their high energy value, rejects could replace fossil fuels and thus reduce CO_2 emissions. At large-scale mills the incineration of rejects could be economically feasible (JRC, 1998).

Deinking residue, which contains lots of ink particles, is not generally considered a hazardous waste and is therefore dumped or incinerated. Depending on the grade produced, paper residue from clarification stages or mechanical purification is returned to the process (Luttmer, 1996). In the case of corrugated board, secondary sludge from wastewater treatment is returned to the process (JRC, 1998).

Figure 3.6 illustrates one possible water circulation in recycled-fiber pulping. In this example, water that is circulated can be divided into three groups: clean, moderately contaminated, and contaminated. These loops are separated by thickening stages, which reduce the carryover of the water to the next section. The multi-loop principle can prevent different chemicals and substances from entering a process in which cleaner water is required. Excess water is fed back to the previous loop, where the water quality does not need to be so high. In this way, water circulation can be almost closed, and in the case of lower grades, such as testliner, it can be totally closed. Generally, without deinking effluent levels of 3–6 m^3/ton are achievable. Internal clarifying is carried out using bow-screening, polydisk filters, or dissolved air flotation as in *Figure 3.6* (Luttmer, 1996; JRC, 1998). Closing the loop raises the water temperature. This has a positive effect on dewatering in the wire part of a paper machine; however, it also provides more suitable conditions for micro-organisms and corrosion. The construction of loops can, of course, be different from that presented in *Figure 3.6*.

Water consumption by a recycled-fiber-based paper mill is less than 2–10 m^3/ton without deinking and 5–30 m^3/ton with deinking. Wastewater from recycled fiber processing consists mainly of water from reject separation using screens and centrifucal cleaners, filtrates from washers, water from thickening and deinking, and excess white water (Luttmer, 1996; JRC, 1998).

Required emission levels from a deinking pulp (DIP) mill are as follows:

Water

- BOD: 0.05–0.13 kg/ADt
- COD: 3–4.5 kg/ADt
- AOX: <0.005 kg/ADt
- N: 0.02–0.06 kg/ADt
- P: 0.005–0.01 kg/ADt

Air

- SO_2: 0.05–1.5 kgS/ADt
- TRS: 0.01–0.05 kgS/ADt
- NO_X : 0.6–1.5 kg/ADt

Waste

- Nonhazardous waste to landfills: 60–150 kg/ADt (JRC, 1998)

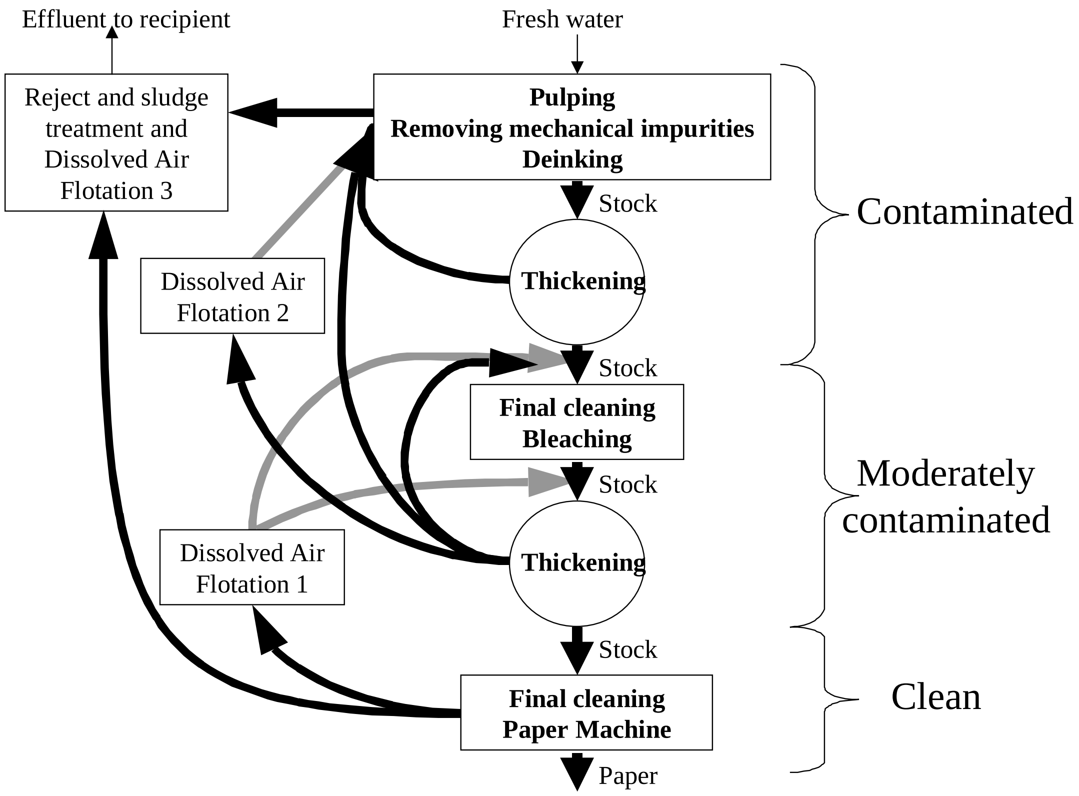

Figure 3.6. Water circulation in recycled fiber pulping.

COD emissions are much higher from plants with deinking than from plants without it because deinking and bleaching release large portions of the COD retained in the waste paper in previous processing (Luttmer, 1996). Generally, emissions are low. The amount of waste to landfills can be high if the quality requirements of the deinking pulp are demanding. Emissions to the air depend on the support fuel used on-site in energy production.

Printing ink in waste paper is the main source of emissions of heavy metals. The amounts are higher when deinking is included. The main sources of AOX are wet-strength chemicals and waste paper containing chlorine-bleached pulp (Luttmer, 1996).

Electrical energy consumption in recycled-fiber pulping is 300–500 kWh, if consumption in papermaking is excluded. Pumping consumes about 50%; screening and dispersing together consume 33%; and pulping, agitation, and ventilation consume 20% (Ministry of the Environment, 1997).

3.3.2 Discussion on best practices in recycled-fiber pulping

The quality of recovered paper should meet the requirements of the final product. Methods of collecting and assorting waste paper play a major role in the quality. Defining the best practices in those activities is, however, beyond the scope of this study. If every mill received the most suitable raw material for its purposes the environment would benefit without any investments in working capital.

According to the Swedish Environmental Protection Agency (1997), the emission levels to water from a deinked-recycled-fiber-based paper mill without internal purification methods are approximately 20 m^3/ton of effluent, 40–90 kg/ton of COD, and 20–40 kg/ton of BOD. The required emission levels cannot be met using the most efficient external treatment methods alone. According to Luttmer (1996), recycled-fiber-based mills with a low effluent load can use low load activated sludge treatment with removal efficiencies of 95–99% for BOD and 80–85% for COD. These figures are valid only when high-concentration effluent is treated. Achieving this requires internal circulation of water. Probably the most economic way to meet required emission levels is to cut 50% of the water consumption by reusing condensates and to introduce the most modern aerobic biological treatment methods. Combined anaerobic and aerobic treatment leads to greater efficiencies. However, anaerobic treatment is recommended only for non-deinked grades (Swedish Environmental Protection, Agency 1997; Luttmer, 1996).

The separation of cooling waters and fiber circulation is more expensive at existing mills than at new mills. However, to meet required emission levels, these measures must be carried out. Also, spill collection, improvements in thickening and recycling of secondary sludge can be costly in existing mills. The latter of these, however, is still a very efficient way to reduce total suspended solids (Confederation of European Paper Industries, 1997).

3.3.3 Other environmental practices in recycled-fiber pulping

Aerobic treatment can be partially retrofitted for anaerobic treatment if the treatment plant is overloaded (JRC, 1998). The anaerobic method becomes more attractive if the water circulation loop is closed (Luttmer, 1996).

Fiber fractionating and separate treatment for the different fractions in stock preparation is possible for non-deinked grades. Longer fibers are more important for binding and do not require extremely careful treatment. One solution may be to properly clean only the short fibers in order to decrease energy consumption; another solution may be to refine only the long fiber fraction to improve pulp strength and paper machine efficiency. The solution chosen depends on end-user requirements (JRC, 1998). Retrofitting stock preparation may be costly at existing mills.

Dissolved air flotation is the most effective clarifying method (JRC, 1998). Multi-stage flotation to recover fibers and fillers is preferred (Luttmer, 1996).

Using a totally closed water loop with anaerobic in-line treatment for treating brown grades is interesting because the anaerobic method produces little sludge, and the sludge can be burned with the methane generated in the process.

A multistage cleaning process is used to reduce the usable material in the deinking residue. A flotation system can combine two flotation stages to remove fibers from deinking foam (European Commission, 1996). If incinerated, deinking residue ash can serve as a resource for building materials (Luttmer, 1996).

It is important that the ink-manufacturing industry develop inks without harmful heavy metals. Removing them using end-of-pipe technologies is expensive (Luttmer, 1996).

3.3.4 Possible future

In the future, supercritical water oxidation may be an alternative to sludge incineration. Clean water, CO_2, and pure ash are generated, and hazardous compounds are destroyed (Luttmer, 1996).

Recyclability of coating chemicals and fillers is one of the biggest challenges for the future. Research for commercial solutions is under way. Ink removal in the deinking process could be combined with removal of fillers from the paper.

Tests have shown that enzymes have the potential to improve deinking, bleaching, dewatering, and slime control (Luttmer, 1996). Commercial solutions may be available in the future.

4. Paper and board

4.1 Papermaking process and its environmental impact

Sections of paper-making machines include the stock preparation section, the wire section, the press section, the drying section, and the reeler. Calenders, coaters, winders, and rewinders are optional units.

The main raw materials used in papermaking is either a combination of pulps or a single type of pulp, as described in the previous sections. In stock preparation, pulp is refined, cleaned, and diluted to a very low consistency. Chemicals and fillers are added.

Low pulp consistency permits the formation of a thin but even fiber distribution on the wire section. There, the pulp is dewatered to a fiber content of around 20%. The paper web is compressed in the press section to remove more water and strengthen interfiber bonds and the fiber content of the paper web is 35–52%. In the drying section, the paper web is further dried to 90–95% (Ministry of the Environment, 1997). Figure 4.1 shows one example of water circulation and fiber flow in a paper machine.

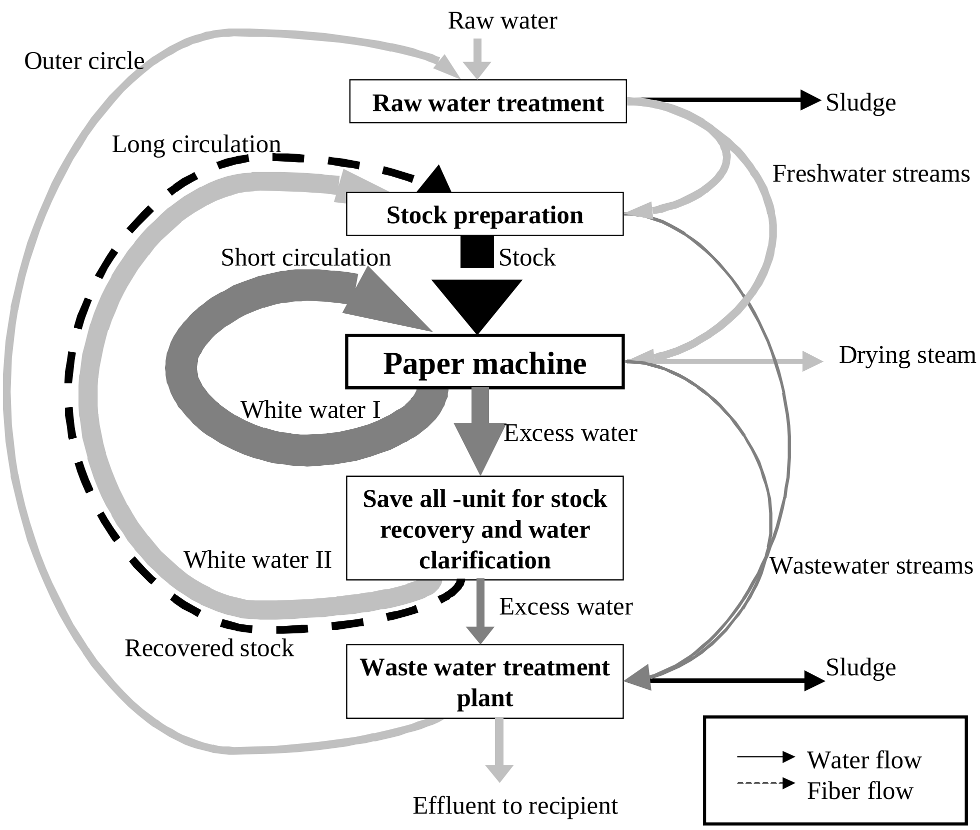

Figure 4.1. Example of water and fiber flows in paper machines.

In the calendering, sizing, and coating processes the appearance and printing properties of the paper are enhanced to meet the customer's requirements. Several technologies for these processes exist. When paper is coated, the coating color, which consists mainly of pigments and bonding agents, can comprise up to 50% of the total weight of the paper.

Water filtrate removed from the wire is called white water. Part of it (white water I) is not treated at all and is reused for pulp dilution. Part of the water is treated (e.g., in a save-all unit) to recover usable fibers and produce cleaner water (white water II) for more demanding uses, even for replacing fresh water. Partially treated water is used in mechanical or recycled-fiber pulp mills in integrated mills but not in chemical pulp mills. Fresh water is normally used for sealing and lubrication and as shower water on the wire section. The more fresh water used, the more excess white water that must be discharged. Internal wastewater treatment (see *Figure 4.1*) would be a big step toward a closed paper mill.

Increasing the degree of closure does not significantly reduce the amount of organic substances in the effluent, the concentration of organic substances simply increases. However, in this case, biological treatment can be very efficient. If effluent volume is high and chemical pulp is used as a raw material, the concentration of organic substances can be so low that biological treatment has only a minor effect on emissions (Ministry of the Environment, 1997; Swedish Environmental Protection Agency, 1997).

Required emission levels from a non-integrated fine paper mill (according to Jaakko Pöyry, 1998) are as follows:

Water

- BOD: 0.05–0.7 kg/ADt
- COD: 0.5–3.0 kg/ADt
- AOX: < 0.005 kg/ADt
- N: 0.1–0.2 kg/ADt
- P: 0.01–0.02 kg/ADt

Air

- SO_2: 0.05–2.6 kgS/ADt
- TRS: 0.1–0.3 kgS/ADt
- NO_X: 0.9–3.0 kg/ADt

Waste

- Nonhazardous waste to landfills: 40–100 kg/ADt

The main discharges are rejects from pulp cleaning, excess white water, and temporary spills (Ministry of the Environment, 1997). Most of the discharged suspended matter is separated during primary treatment, and the separated sludge is dewatered and disposed of. Discharges to the air occur mainly from the dying by air and from power plant fluid gases. COD and BOD originate from pulp refining or, in an integrated mill, from substances carried over from the pulping process. Recovering the waste from coating color production is important for enabling incineration of sludge (Ministry of the Environment, 1997).

Some VOCs emanate from solvents used in coating operations and cleaning machine fabrics. The use of formaldehyde-containing wet-strength agents is another source of VOCs (BAT).

Water consumption in a paper mill is normally 5–50 m^3/ton (Lahti-Nuuttila, 1998). The energy consumption of a paper mill is under 2 MJ/ton. Approximately 90% of the heat is used for drying (Ministry of the Environment, 1997). The electricity consumption of a non-integrated paper mill is approximately 0.7 MWh/ton. Pumping accounts for 25% of this amount and is the greatest single electricity consumer.

4.2 Best practices in papermaking

As in the case of chemical pulping, the numerical data necessary for discussing environmental best practices in papermaking are not available. The nature of the process is different from that of chemical pulping. The environmental goals in papermaking are to reduce water consumption, to improve energy efficiency, and to reduce material consumption. One clear difference from the environmental techniques used in pulping is that these goals improve both environmental performance and the cost performance of producers.

If the annual cost of an environmental measure is low or even negative and the measure has no negative impacts on product quality, it is justified to claim the measure as an environmental best practice. One example is the reduction of the basis weight of paper or board. In the case of newsprint, basis weight has decreased from 52 g/m^2 to 40 g/m^2 in two decades as a result of improved knowledge of fiber physics. Emissions per square meter of paper have decreased in the manufacturing process and in transportation. Moreover, less forest is affected. If lean material techniques are adopted globally, the amount of waste paper sent to landfills decrease. In the example presented in *Figure 4.2*, the numbers are based on average required emission levels in mechanical and chemical pulping, and wood consumption in these processes.

In the future, the importance of lean material techniques is likely to increase. The reason is that absolute emissions from manufacturing processes continue to decrease, and consequently transportation and forestry become more important sources of environmental impacts (assuming that emissions from transportation do not decrease considerably). According to environmental reports from the SCA (1998) and Södra (1998), air emissions from transportation are almost equal to emissions from manufacturing. Although the plants of these companies are located far from the main market, Central Europe, the share of the Nordic pulp and paper production in total EU production is considerable. The conclusion drawn from the environmental reports of the largest companies in Europe is that transportation is gaining more and more importance in the environmental debate. For instance, catalytic converters and low-sulfur oil have been introduced to reduce NO_x and sulfur emissions in transportation.

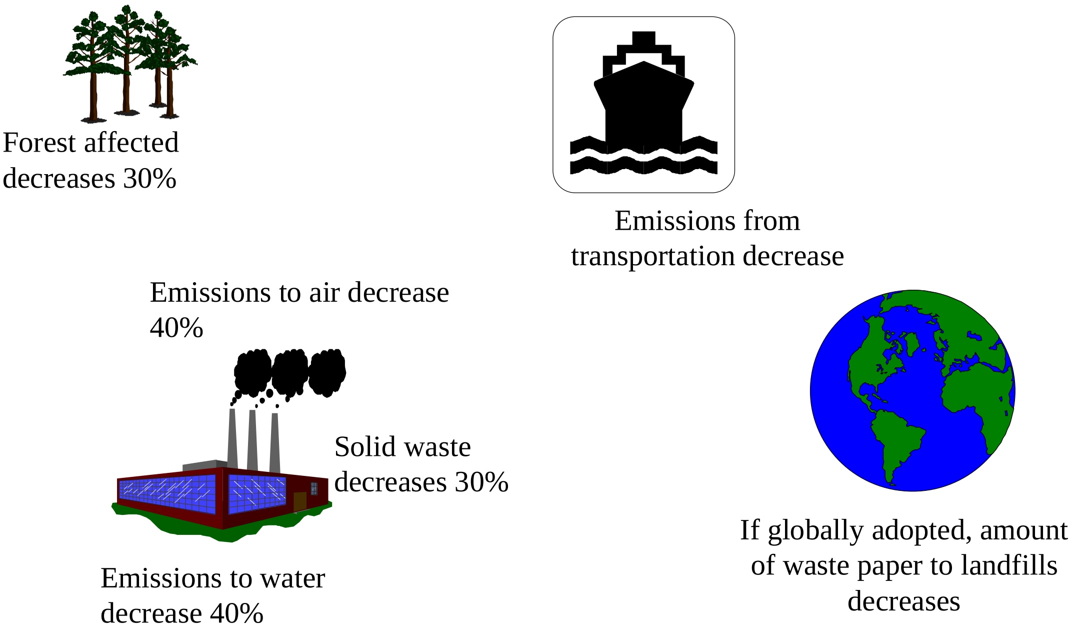

Figure 4.2. Dematerialization: Influence on environment if paper grammage can be lowered by 20% by offsetting one-third of chemical pulp with mechanical pulp.

Although the pulp and paper companies have recently begun to stress the dematerialization issue in their environmental reports, there are several reasons why companies probably will not make this issue public in the future (MoDo, 1998; Amcor, 1998; Enso, 1997a, 1997b; Metsä-Serla, 1998). First is the value of secrecy. For the companies, the benefit of production cost savings is more important than the environmental benefit. Companies do not want reveal their techniques. Second is the partial ownership of the value chain. For instance, savings in fiber consumption are quite difficult to convert into savings in environmental costs if a company does not manufacture all the raw materials. Also, the reductions in air emissions can be highest in the delivery of printed paper. For example, when air freight is used, a great deal of fuel is saved when the paper basis weight is lower. Third, figures used in the pulp and paper industry are ton based: although environmental accounting is a developing field, the emissions are still presented per ton of product. However, the number of square meters of paper produced for a certain purpose is more important than the number of tons produced. *Figure 4.3* gives an exaggerated example of the contradiction implicit in using both ton-based and square-meter-based figures. In the text below *Figure 4.3* is a description of lean material techniques that can be considered as best practices in papermaking. However, some of these techniques are not attractive in the case of existing mills. Because of the patenting and know-how required, licensing may be the only way to utilize such techniques.

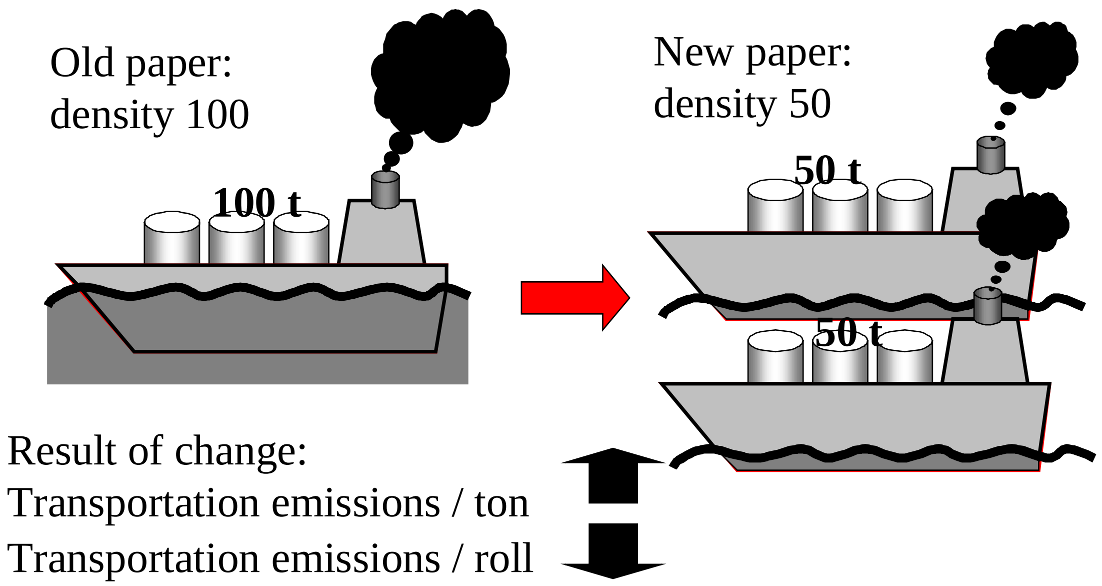

Figure 4.3. The transportation paradox in the change to a lean resource paper with similar functional properties and similar volume but 50% density and consequently 50% grammage compared with the original. In both cases *one ton* of paper is transported, but in the second case the *area* is doubled.

In normal magazine-paper calendering, under high temperature and nip pressure, paper is compressed and loses part of its light-scattering surfaces, and thus the opacity of the paper decreases. The high temperature softens the lignin and consequently the stiffness of paper decreases. By using a special type of soft calender, these problems can be avoided. Paper can be produced that has a lower basis weight but maintains its original functional properties (SCA patent) (Enso, 1997a, 1997b).

Metsä-Serla has introduced a fine paper in which mechanical fiber is used, resulting in considerable basis weight reduction. The paper contains mechanical aspen pulp. Because of its high bulk and high opacity, the mechanical pulp provides high stiffness. The process for producing this kind of paper has been patented.

The bending stiffness of the paper is directly proportional to the paper’s elasticity modulus and to its thickness to the third power. There are two principles to lowering basis weight. First, the elasticity modulus are important in the surface layer of the paper. Because of its higher modulus compared with that of mechanical pulp, chemical pulp is used in the surface layers. Second, by using mechanical pulp or CTMP in the middle layer, the same thickness can be achieved using less fiber. However, yellowing is a problem associated with mechanical pulp. Then the problem with copy paper is to get it bright enough. With coated papers this problem does not exist (Häggblom-Ahnger and Eklund, 1998).

In the case of the patented techniques of multi-layer web forming, one accessible technology is the multi-layer headbox. Multi-layer headboxes are used most often in tissue manufacturing but can also be used in the production of printing paper. In cartonboard manufacturing, several wires are used to achieve multi-layer construction. Folding boxboard is made using mechanical pulp in the middle layer of the board. Solid bleached sulfate (SBS) board producers, which have traditionally only used bleached pulp, have started to use mechanical pulp in the middle layer. Usually, 10–20% less fiber is needed to achieve the same functional properties for the board. CTMP pulp is commonly used by traditional SBS producers (Enso, 1997a, 1997b; Stora patent; expert opinions).

Using dry-strength chemicals such as starch is one way to reduce basis weight. However, this method results in a higher amount of starch in the process and has other environmentally related effects. An alternative method is to add fines to improve opacity. High reductions in basis weight (around 20%) have been achieved under laboratory conditions. In real-world manufacturing, this measure is still very difficult to carry out (Retulainen and Nieminen, 1996).

Producing as little broke as possible is another lean material technique. Management and the skills of the work force play a central role in this technique. Manufacturers of paper machines are developing technologies that provide a higher capacity utilization rate. For instance, the reeling process is very sensitive to cuts (Valmet, 1999; expert opinions). New technology is the best practice for new mills, but at existing mills training of the employees for lean production is probably the most efficient measure.

In addition to lean material techniques, techniques that aim at reducing energy and water consumption are numerous in papermaking.

The first such technique is related to lean material technologies. In mechanical pulping, producers have traditionally used long fibers and a high amount of energy to achieve the strength properties required for magazine papers and newsprint. Because of its opacity and bulk properties, when mechanical pulp is used the fiber mixture can be modified. For instance, short and thick fibers can be used instead of long fibers, groundwood pulping can be used instead of refining, or mild mechanical treatment can be used instead of hard mechanical treatment. The result is lower energy consumption. According to experts, nonconiferous wood and short fractions of coniferous wood can partially replace long fractions of coniferous wood.

Environmental benefits only partially explain the current trend toward closed water circulation. The higher the degree of closure, the higher the temperature of process waters. Energy consumption is lower and retention on the wire section is better. The costs of pumping and treating fresh water and effluent can be reduced. Furthermore, on the one hand, the higher degree of water circulation closure is a logical consequence of more efficient fiber recovery. This results in lower material consumption. On the other hand, the number of pumps required for recycling the water increases as the loop is closed. This has an adverse effect on energy consumption (Kettunen, 1999a, 1999b).

Nevertheless, the operational savings from greater closure should be considerable. It has been estimated that reducing freshwater use from 20 m^3 to 10 m^3 per ton requires an investment of around 10–12 million ECU (Swedish Environmental Protection Agency, 1997). Investments are made in better clarifying devices and in the separation of clean and contaminated water.

Water consumption was reduced by 30% and TSS were reduced by 50% at a Finnish paper mill when an additional disk filter was installed (Finnish Forest Industry Federation, 1998). Precoat disk filters are designed to produce cloudy and clear water through three or four separation stages (JRC, 1998).

For improving the internal purification efficiency of process water in an integrated mill, excess white water should be removed between the mechanical pulp mill and stock preparation. Here, the pollutant content is perhaps higher than at any other point in the process and the cleaning efficiency better (Jaakko Pöyry, 1998). To improve fiber recovery, the excess white water that is removed from the process should be clear, not cloudy, white water (JRC, 1998).

By adding retention agents such as polyelectrolytes, the load in the fiber recovery can be reduced. Retention agents can also be used in sludge dewatering (Luttmer, 1996).

Retention, recyclability, and biodegradability are the most important characteristics of chemicals used in papermaking. The better the retention, the fewer the chemicals in the wastewater. The more biodegradable the chemicals are, the more efficiently they can be destroyed in the external treatment plant (European Commission, 1994).

As much as a 30% decrease in freshwater consumption has been achieved by recycling the sealing and cooling waters. Less of an investment is needed than with internal purification methods (Finnish Forest Industry Federation, 1991–1998). Recycling these waters requires that cooling water be kept separate from other process waters. Cooling water can be reused as fresh water or as cooling water in places where higher temperatures are allowed (European Commission, 1996).

Coating wastewater should be pretreated separately. Pretreatment can be through chemical precipitation or membrane filtration as ultrafiltration. Ultrafiltration is used for recovering the coating color pigments and substances with high molecular weight (Ministry of the Environment, 1997). The advantage of ultrafiltration is the possibility of recycling the coating chemicals. The investment cost of ultrafiltration for low liquid flows is 0.2–0.3 million ECU (JRC, 1998).

With closed water circulation, chemical balance and slime may be problems. Chemicals are needed to control the increasing biological activity. The situation can be controlled most easily in a simple machine producing one or only few grades of paper. It is important that incoming pulp is thickened properly, as this is a way of enabling greater closure of the flows of the mill.

With a high degree of closure, overflows become more common and better control methods are required. When the degree of closure is low, the water balance can be controlled by adjusting the amount of incoming fresh water (Swedish Environmental Protection Agency, 1997). The broke chest should be long enough to store at least three hours of full production (JRC, 1998).

A high degree of closure may raise the temperature of process waters too high. Cooling towers are needed, requiring extra investments (Swedish Environmental Protection Agency, 1997). Using internal measures to close the water circulation is not necessarily economically attractive in existing mills (Finnish Forest Industry Federation, 1991–1998).

Approximately 50% of drying air can be recovered. The payback time for an investment that permits such recovery is short (JRC, 1998).

Shoe presses decrease energy consumption in the drying section by 15%. The technology enables longer nips and a better dewatering effect. Using the shoe press also improves the runnability of the machine; therefore, material and energy consumption per ton are improved as well. Installing a shoe press does not require costly investments, and it can be used with both old and new machines (JRC, 1998).

The sizing process generates a hydrofobic layer on the paper and increases the paper's surface strength. Resins are commonly used in sizing but are toxic to bacteria. Instead, modified starches should be used for sizing, as they are biodegradable and non-toxic. The starches should be applied using a size press (JRC, 1998). Formaldehyde is a problem with respect to air emissions; low-formaldehyde resins are available for improving wet strength. Finally, the solvent-based coatings that are usually used in the specialty paper sector should be avoided.

At non-integrated fine paper mills, biological treatment of effluent is not always necessary. Required emission levels can often be met using chemical treatment. Investment costs of chemical treatment are much lower than those of biological treatment. At an integrated paper and mechanical pulp mill, chemical treatment can be extended by using biological post aeration. BOD can be reduced by 30% and investment costs are only around 0.2 million ECU (Finnish Forest Industry Federation, 1991–1998).

Paper that meets certain quality requirements can usually be produced using several combinations of different pulps. From the environmental point of view, deciding the best combination of raw material is very complicated. For instance, recycled pulp is preferred to chemical pulp in most recommendations. However, it has been shown that with a somewhat cleaner chemical pulping process than is currently used, the use of chemical pulp becomes preferable with respect to the environment because waste paper collection requires a significant amount of transportation. Instead of being recycled, the paper could be used in energy production, replacing fossil fuels and their characteristic emissions (Weaver et al., 1997). The alternative role of mechanical pulp discussed above increases the complexity of this issue.

4.3 Other environmental practices in papermaking

Ultrafiltration used as an internal purification method has reduced the amount of effluent (Lahti-Nuuttila, 1998). Ultrafiltration can be used to reach a higher degree of closure of the mill. The investment costs of ultrafiltration are high, around 6–8 million ECU, and annual operating costs are around 1 million ECU.

Composting biogenic waste is possible. Fiber waste can also be used in the construction industry. Concerning end-of-pipe technologies, the possible best practices in the paper industry are largely the same as those in the pulping industry.

4.4 Possible future

Regarding dematerialization, one possibility for reducing the basis weight is to convert the passive role of pigments and fillers in bonding to a more active one. This would reduce the need for fibers. Commercial applications are not yet feasible; however, according to Enso's annual report (Enso, 1997a, 1977b), when precipitated calcium carbonate (PCC) is used as a filler, the basis weight can be lowered.

One interesting technique that is not yet in its commercial stage is dry coating. In dry coating, the coating color kitchen is not needed in its present form. The drop in energy consumption for drying is around 90%, and 50% less pigment is needed. During dry coating, the pigments are heated in a special manner and an electric field transfers the pigments to the paper surface. Small basic particles can be bonded together without any bonding agents.

One very interesting approach in environmental issues is the minimill concept. The minimill concept is characterized by the location of mills near markets and raw material, close cooperation with the customer, and highly standardized and modulated machine construction. The last of these means that the machines are simple and contain very few or no tailor-made parts. In this way, investment costs are lower. The competitive edge arises not from the differentiated product, but from the close relationship with the customer. By using local raw materials and supplying products to local customers, the discharges from transportation can be cut dramatically. The amount of different chemicals and transportation involved in supplying them can be reduced as a result of the narrower grade scale. Among the products that could be made according to this concept are newsprint, tissue, and corrugated board (KTM, 1994; Kettunen, 1999a, 1999b).

The minimill concept combined with the use of virgin fiber pulp would create a new mass production paradigm, replacing the old integrate paradigm. Virgin fiber, as well as mechanical pulp, could be supplied from a large mill. Transportation emissions would be much lower than if wood were supplied to many small or middle-sized pulping units. With respect to environmental investments, large mills operate with economies of scale. Abandonment of integrated pulp lines would also reduce the negative effects of the water discharged from the pulp mill. Moreover, energy consumption can be lower because drying of pulp is not necessary in an integrated mill.

5. Mechanical wood industry – Primary goods

The branches of the mechanical forest industry studied for this document are the sawn timber, wood panel, and wood furniture manufacturing sectors. The last of these is discussed in a separate section because of its special characteristics.

Of the forest cluster branches, the mechanical forest industry has the strongest connections to the other forest-related industries as far as raw material is concerned. Almost 100% of the raw material used consists of wood. Around 40% of wood processed in sawn timber and plywood production ends up in the final product. Over 40–50% of the processed wood is used as a raw material in the other mechanical forest industry branches or in pulp production. Another 7–16% is used as biofuel.

Because of this high utilization of wood and the low consumption of other raw materials, the mechanical forest industry has a very good environmental image. The environmental problems are local, with noise and sawdust being perhaps the most notable. Energy consumption is another problem that cannot be neglected.

5.1 Environmental best practices in sawn timber manufacturing

The construction and furniture industries are the principal consumers of sawn timber. The construction industry is assumed to account for 80% of consumption.

The sawn timber manufacturing process consists of debarking, cutting, and shaping of raw timber (*Figure 5.1*). All these processes contribute to emissions (UN, 1983).

Debarking has a slightly different function in the mechanical forest industry than in chemical wood processing. In the latter, proper debarking is a prerequisite for acceptable pulp quality. In the former, the bark of the wood can cause problems in sawing, reducing efficiency. As in chemical wood processing, both wet and dry debarking are available. In one American sawmill, emissions to water from wet debarking were only 0.02 kg/m^3 of BOD, considerably lower than the typical wet debarking emissions of 2 kg/m^3 of BOD in the processing of pulpwood (UN, 1983).

During the summer period, logs are watered when stored to prevent so-called blue-staining. It is, however, possible to entirely abandon watering. For instance, watering can be reduced through modifications in production systems. Another option is to close the watering system. Dissolved substances from the wood can be eliminated from the effluent (KTM, 1994). Wastewater discharges can be eliminated almost completely by developing procedures to recycle effluent and stormwater runoff, directing it back into the mill's process water (Weyerhaeuser, 1998). If the water is not recycled, a settling pond can be used as an external treatment (Metsäliitto, 1999).

The use of agents to prevent blue-staining has decreased rapidly, with 1998 consumption levels reaching only 10% of 1990 levels (Finnish Forest Industry Federation, 1998). The main reason for this has been the decreased lead times for processed wood. At present, sawn goods are not stored for as long a time prior to drying (Metsäliitto, 1999).

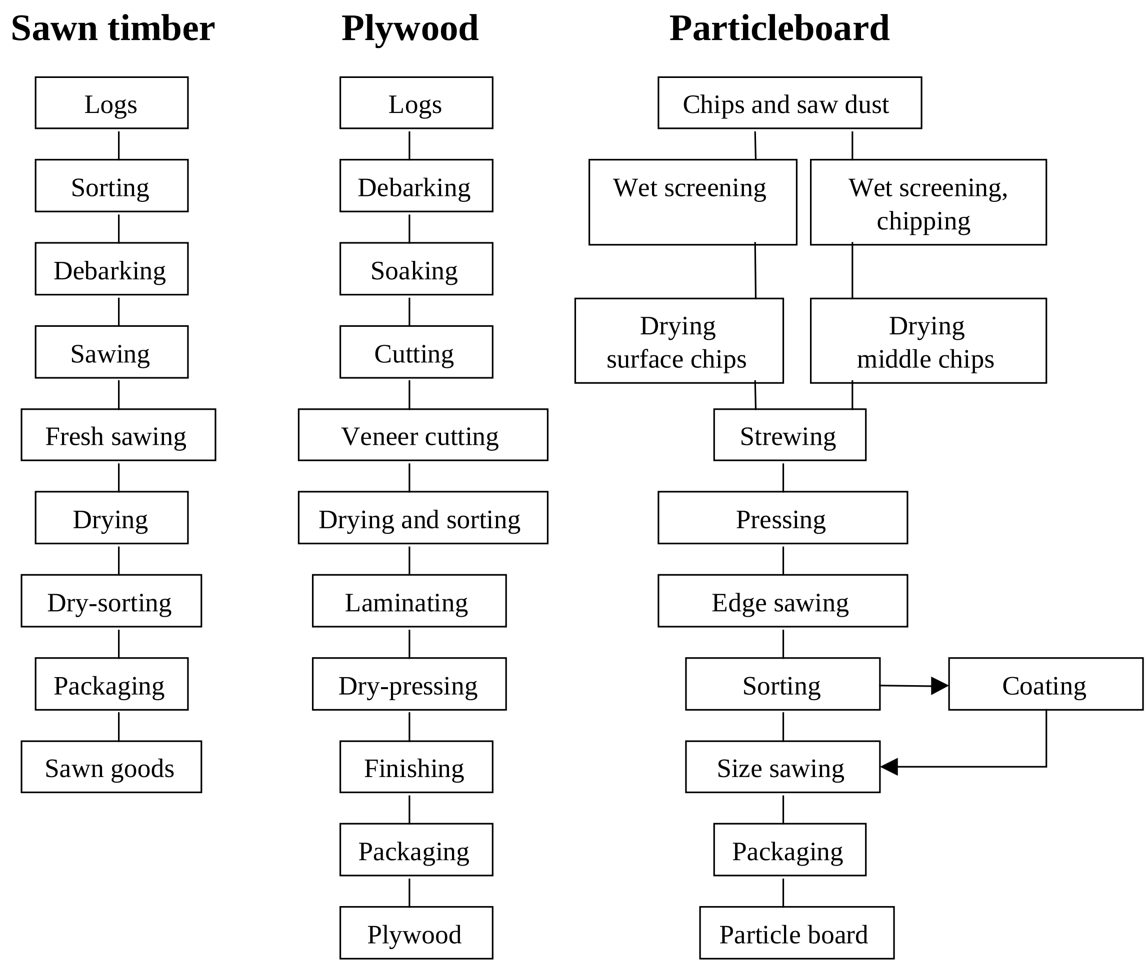

Figure 5.1. Production chains in the mechanical wood industry.

Since 1970, the use efficiency of raw material has grown steadily in sawn timber production. In the USA, the ratio of produced lumber to roundwood used has risen from 33% in 1970 to 42% in 1993. According to Ausebel (1998), the techniques that have enabled this development are best open face technology, the edge-glue and rip method in edging, and the saw-dry-rip method for processing nonconiferous wood. Sharper and more stable blades have also contributed to this development. The sawn timber industry has switched from the use of frame saws to the use of rim and circle saws. This has further improved the utilization efficiency of wood material (KTM, 1994).

After sawing, air seasoning or kiln drying is used for drying wood. Small amounts of VOCs may be emitted during air seasoning. On the other hand, the fuels used in kiln drying generate other air emissions (UN, 1983). Nevertheless, mills are switching from air seasoning to kiln drying, which has resulted in rapid growth in the use of chamber dryers (KTM, 1994).

The possibility of incinerating wood residues has increased as a result of developments in the chemical treatment of wood. A complete abandonment of protective measures is also possible as a result of developments in drying technologies (KTM, 1994).

A non-toxic decay-preventing aid has been developed in Finland to diminish the mechanical forest industry's impact on the environment. The idea is to bind iron and manganite, both of which are catalysts in the decay process (KTM, 1994). The principle has been accepted and further developed in the sawn timber industry (Koskisen, 1999).

According to an environmental report from a Finnish company in the mechanical forest industry, VOC emissions from sawn timber production are around 0.5 kg/ton. This figure is quite close to the VOC emissions from chemical pulping, but is only around 5% of the VOC emissions per ton from the printing industry.

Solid waste from the mechanical forest industry accounts for approximately 1% of used wood. The majority of the solid waste is transported to landfills and consists of sludge, bark, and ash. More efficient sorting and reuse of waste generated at sawmills have significantly reduced the volume of landfill waste.

Emissions to water from sawmills are minor (Finnish Forest Industry Federation, 1998). Solid fuel boilers with cyclone ejectors, electrostatic filters, and wet scrubbers can be used to prevent dust emissions.

Production of sawn timber consumes approximately 300–500 kWh/ m^3 of energy. Drying of sawn timber accounts for over 60% of the total. Because the residues can be used as fuel, sawmills are usually more than self-sufficient with respect to energy. Surplus energy consisting of this fuel and the heat produced from it is normally over 400 kWh/m^3. Surplus energy depends on the ratio of wood residues for use as a raw material to wood residues for energy production (Finnish Forest Industry Federation, 1998).

5.2 Environmental best practices in plywood manufacturing

Plywood is produced from turned wood veneers that are glued together. Adjacent veneers are set perpendicular to each other. This structure results in a strong panel. Plywood products are used where high strength is required. *Figure 5.1* presents the manufacturing process for plywood (Metsäliitto, 1999).

Emissions to air and water are low in the veneer and plywood industries. Emissions from plywood manufacturing are mainly from the drying process, where steam and airborne particulates are common. The industry has made great efforts to reduce VOCs and formaldehyde emissions, in particular, from its products and manufacturing operations (Industry Canada, 1999). Phenol formaldehyde, made from phenol resin and a hardening agent, is used in glue. Glue treatment can be a closed process (Metsäliitto, 1999).

In a plywood plant, the methods for reducing effluents are as follows:

- Complete recycling of glue waste and its reuse in preparing the glue
- Complete closure of the water system in log conditioning
- Closure of the dryer washing operation (UN, 1983)

Using a flotation system for mechanical treatment of soaking water can decrease TSS emissions from soaking by over 90%. Glue solids in the wastewater from glue mixing and washing of application equipment are treated in settling ponds or septic tanks. The dissolved organic and chemical waste can be treated in a municipal treatment plant or incinerated. The latter is a very costly option (UN, 1983).

By improving the sorting of waste, the amount of solid waste to landfills can be reduced significantly. Solid waste composting is also possible (Metsäliitto, 1999). Sawdust can be incinerated.

Scrubbers are used in chamber drying to clean exhaust gases (Metsäliitto, 1999). Electrostatic precipitation is suitable for treating flue gases. Solvent emissions containing VOCs can be led to a boiler used for energy production (Schauman Wood, 1999).

Production of plywood consumes approximately 900kWh/m^3 of energy. Water consumption is around 3.5 m^3/m^3, approximately four times higher than in sawn timber production. Compared with sawn timber production, approximately 0.4 m^3/m^3 more wood is needed, but, on the other hand, 0.4 m^3 more wood can be used in energy production (Metsäliitto, 1999). There is around 5 kg/m^3 of solid waste in sawn timber production versus 7 kg/m^3 in plywood production. Emissions to water in one Finnish plywood mill were around 0.3 kg/ton of BOD (Finnish Forest Industry Federation, 1998).

5.3 Environmental best practices in particleboard manufacturing

Instead of incineration or landfilling, wood chips and sawdust are used as raw materials in particleboard, fiberboard, and pulp production. The furniture building industry is the main consumer of particleboard. *Figure 5.1* presents the manufacturing process for particleboard.

In particleboard manufacturing, wood chips are glued and pressed to form various panel types. The smallest chips are used in the surface layer of the panel to improve smoothness and tightness for coating operation (Metsäliitto, 1999).

The adhesives used in particleboard manufacturing consume more formaldehyde than do those used in plywood manufacturing. The water emission problem is similar to that of the plywood industry because the equipment used for mixing and applying glue must be washed (UN, 1983).

Particleboard manufacturing tends to produce greater particulate emissions during the drying process than does the manufacturing of other wood-based panels because of the smaller particles involved. Pollutants include nitrogen oxides, sulfur oxides, carbon monoxide, formaldehyde, and other VOCs (Industry Canada, 1999).

Recently installed technologies for dryers include partial press enclosures to capture emissions and the use of exhaust air for combustion in the boiler plant. Particulates in the finishing areas are picked up by conventional dust-collection equipment. Other conventional technologies include primary and secondary cyclones, multicyclones, wet dust collectors, dry and wet electrostatic precipitators, baghouses, and electrostatic filter beds (Industry Canada, 1999). The techniques are more or less the same as in the chemical wood processing sector.

Energy consumption and emissions of NO_x and SO_2 from particleboard manufacturing per cubic meter are relatively high compared with those in the other forest cluster branches. Emission figures are not readily available because of the common practice of mixing these figures with those of other types of board manufacturing. According to the environmental reports of two Finnish producers, NO_x emissions are 0.3–0.5 kg/m^3 and SO_2 emissions are 0.7-0.9 kg/m^3. These emissions are probably mainly generated by fuels used for drying. The end-of-pipe technologies used were not reported. Energy consumption in particleboard production is approximately 1.2 MWh/m^3 (Finnish Forest Industry Federation, 1998; Metsäliitto, 1999).

In particleboard and fiberboard manufacturing, the concentration of particulate matter in the emissions to the air should not exceed 50 mg/m^3 from sources other than wood dryers and should not exceed 20 mg/m^3 from wood dryers. The fumes from all pressing, curing, impregnation, and coating operations should be collected and passed through abatement equipment (e.g., a scrubber) to meet these requirements. Formaldehyde emissions should not exceed 5 mg/m^3 from new mills and 20 mg/m^3 from existing mills when wood dryers are excluded. When wood dryers are included, formaldehyde emissions should not exceed 20 mg/m^3 (Department of the Environment, 1995).

5.4 Environmental best practices in fiberboard manufacturing

Fiberboards are divided into three separate classes. High-density fiberboard or hardboard is used in the wood furniture building and construction industries. It is characterized by good water resistance and high strength. Medium-density fiberboard (MDF) and low-density fiberboard or porous board are suitable for wall construction because of their good insulation characteristics (Schauman Wood, 1999).

Fiberboard manufacturing has characteristics from both pulp- and papermaking and particleboard manufacturing. As in particleboard manufacturing, the raw material for fiberboard consists of unused parts of wood from sawmills and plywood mills. This approach makes it an environmentally sound industry (Lilja and Nordström, 1987). Other materials that have been used successfully are waste paper and randomly collected waste wood (Oikarinen et al., 1998). Both wet and dry processes can be used to manufacture fiberboard. The dry process uses less water than the wet process, which is used mainly for high-density fiberboard. Its environmental advantages are obvious.

To facilitate pulping, chips or particles are steam conditioned at an elevated pressure, usually at 10 bars in a digester (Industry Canada, 1999). The wood is subsequently mechanically defibered. High temperatures soften the lignin. The higher the pressure and the lower the heating time, the more organic matter is dissolved into the effluent. Mechanical defibering is performed by using a method that resembles refining in mechanical pulping. The wood material is refined between disks. After defibering, the pulp can be further refined by decreasing the space between the disks (Lilja, 1987).

In the wet process, after refining the pulp is diluted to a 1.5–2% concentration and pulp sheets are formed. Chemicals such as tall oil, phenol resin, and retention chemicals are added. Tall oil is a by-product of chemical pulp production (Lilja, 1987). Adhesion between the fibers is based primarily on their natural tendency to attach to each other (Finnish Forest Industry Federation, 1999).

The water is removed by wires, suctions, or pressing. After dewatering, the dry solids content is 25–40%. For medium- and high-density fiberboards, final dewatering is performed by warm pressing. The board is hardened at a high temperature for 3–8 hours. Low-density fiberboards are not treated by warm pressing but instead are hardened at a temperature of 170°C for two hours. After hardening, the fiber is moistened to a 5–8% moisture content. In the final step the fiberboard may be decorated or impregnated (Lilja, 1987).

Water from the dewatering process is circulated widely. The amount of pressure and length of treatment influence the amount of organic substances in the effluent. Reducing discharged effluent using evaporation is an effective measure if the amount of backwater is low. It is possible to achieve less than 1 m^3/ton of effluent.

Process and quality problems occur when there is a high degree of closure of the process. In some parts of the process, freshwater consumption can be reduced by filtering backwater or abandoning the use of water. For example, mechanical gaskets can be used instead of sealing water. Furthermore, using fresh water in edging is not necessary. Separation of cooling and sealing water, as in the pulp and paper industry, is possible but is economically attractive only at new mills. Spills are also a source of effluents (Lilja, 1987).

In the dry process, fibers are bonded together by an adhesive. The blowlines from the refiners to the dryers are used for blending the adhesive with the fibers. The fibers move at a very high velocity with great turbulence, and thus the adhesive is instantly atomized as it enters the blowline. Urea-formaldehyde adhesives are most commonly used for MDF. New adhesives for faster setting, better bonding, higher moisture content tolerance, higher species tolerance, and lower temperatures are under development. Energy savings in drying and pressing could be substantial. Formaldehyde and other VOC emissions would be reduced significantly.

Drying is performed through tube-type dryers. The high temperatures formerly used in drying have been lowered at the inlet. This has reduced the risk of fire, VOC emissions, and smoke.

Vacuum-assisted formers predominate in mat forming. They deliver dry fibers to an enclosed area above a travelling wire screen while maintaining negative pressure on the underside of the screen. Air travelling through the wire screen causes the mat to form on the screen. After forming, the mat is precompressed for stiffness and strength to pass transfer points and to load into the hot press (Industry Canada, 1999).

Problems with high amounts of effluent ocurr only with the wet process. One method of reducing the effluents is mild pretreatment of the wood before refining. Modifications in refining are also possible. Sedimentation, flotation, evaporation, and settling ponds are usually used as external treatments (Lilja, 1987).

Biological treatment of the wastewater from fiberboard manufacturing is possible but the nutrient balance must be adjusted. It has been suggested that BOD can be reduced by using phenolic resins to aid in coagulation (UN, 1983). Sludge from external treatment can be used as fertilizer (Patinna, 1999)

In Sweden, levels of COD emissions to water were 10–20 kg/ton from the largest producers. Emission levels to water were 5–8 kg/ton for BOD and 0.7–1.7 kg for suspended solids (Lilja, 1987). For the most part, these manufacturers were producing hardboards. In one Finnish fiberboard plant, emissions to water were 4–8 kg/ton for BOD and around twice that for COD using the wet process (Finnish Forest Industry Federation, 1999). With the wet process, BOD emissions per ton of product are significantly higher in fiberboard manufacturing than in the pulp and paper industry.

The dry process generates significantly less liquid waste than does the wet process. One American fiberboard producer solved its wastewater problem by providing for the complete retention of the cauldron washwater. This treatment resulted in a 100% reduction of wastes and required a total annual incremental cost of less than 1% of the annual production value.

For mills that use the wet process, significant incremental costs are associated with biological effluent treatment. An 80% reduction of BOD is estimated to require a total annual incremental cost of 6–14% of the annual production value (UN, 1983). Fiberboard facilities are usually relatively small. Because of its expense, biological treatment cannot be considered as best practice for those in the industry. Biological treatment is used, however (Patinna, 1999).

Emissions of particulate matter and formaldehyde from fiberboard facilities using the dry process are considerable. As in particleboard production, emission of particulates in fiberboard production tends to be greater than in the manufacture of other wood-based panels. The reason is the smaller size of the particles in the drying process (Industry Canada, 1999). Also, formaldehyde is usually released as a result of the application of urea-formaldehyde resin before drying. Formaldehyde is also released from the presses where the resin is activated and the materials are bonded together.

Options for controlling emissions from MDF plants are classified as process modifications or abatement technologies. The two primary areas for their application are the press vents and the dryers, the areas that generate most of the emissions. For formaldehyde control, the process modification for the press vents is to route emissions to the plant's energy system, which operates under high temperature and thus will effectively eliminate the formaldehyde. Process modifications for dryers include reducing temperatures to prevent formaldehyde from being driven off, injecting formaldehyde scavengers, and applying resin after the dryers, using mechanical techniques in place of air-injection systems.

Two abatement technology alternatives that can be effective in reducing both particulate and formaldehyde emissions are biological gas cleaning and thermal oxidation (Environmental Protection Department, 1995). These techniques are discussed in Section 9. For nitrogen oxides, sulfur oxides, and carbon monoxide, the same abatement technologies can be used as in particleboard production (Industry Canada, 1999).

One EU project aims at improving the environmental performance of fiberboard manufacturing. Through the use of high-speed refiners, a 20% reduction in mainline energy consumption may be achieved without a decrease in fiber quality. The use of a double wire pressing machine instead of conventional techniques will lead to an increase in dryness. Larger throughput, reduced electric power consumption through the elimination of the vacuum pumps, and reduced thermal energy requirements are the expected results (Brite-Euram III, 1997).

6. Specialty input and machinery industries

6.1 Chemical suppliers

The environmental impact of different chemicals used in forest-based industries is not well known. The manufacture of those chemicals is not environmentally harmless but cannot be considered significantly harmful. From the forest cluster perspective, the best practice is not to develop the manufacturing process of those chemicals, but to develop chemicals that are recyclable and biodegradable, and are made from renewable raw materials.

One problem in dealing with the part of chemical industry related to forest-based industries is the fragmented customer base. Companies in these industries usually manufacture numerous chemicals, and those for the purposes of forest-based industries are only a small part of the total production.[2] The companies that manufacture pigments and binding agents are perhaps the most important chemical industry companies for the forest cluster. Fillers or coating can account for as much as 50% of the basis weight of the paper.

Pigments are minerals that are converted in some way. Kaolin, calcium carbonate, talc, gypsum, and titanium dioxide are the pigments used. The first two are predominant. Mineral mining is an environmentally sound process if dry processing is used. In that case there are no emissions to water. Only rainwater or groundwater may temporary come into contact with pollutants, in which case the water must be pumped out. Dry dust collectors are used for eliminating dust discharges (Costle *et al*., 1979).

In a simple procedure, converting can be limited to the refining of pigments to a finer form and the removal of impurities. Refining consumes 0.2 –0.4 MWh/ton of energy.

Precipitated calcium carbonate (PCC) is a more advanced form of pigment. Its crystal structure is more suitable for papermaking, providing opportunities for basis weight reductions.

The most common binding agents are starch, latex, and carboxyl methane cellulose (CMC). Starch is also used as a sizing agent. In starch and latex processing, the pretreatment of water is very important because of the high water consumption. Part of the raw materials is in gaseous form, and some equipment to prevent its release to the air has to be used. Dust emissions can be abated effectively using fabric filters. Oxidization of starch can be performed without the use of organic chlorine compounds.

Biocide concentrations of paper chemicals have been reduced. For the most part, raw materials are renewable.

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[2] Conclusion drawn from annual reports and the environmental reports of some chemical manufacturing companies.

The environmental impact of processing paper chemicals is low. The focus in environmental protection is on preventing damages (Raisio, 1998).

6.2 Machinery suppliers

The machinery supplying industry represents the metal industry. The productive processes of this industry cause some environmental problems. The value added to the raw metal by the processes is very high. The environmental goal of the machinery industry is to provide acceptable environmental solutions to the customers (Valmet, 1998). This objective currently has priority over a clear protective process in the machinery industry.

7. Printing on paper and packages

7.1 Printing and its environmental impact

Printing and packaging companies convert paper or paperboard into its final form. The end product will either carry information or protect another product, or both. Because of the numerous paper and board grades and end-customer requirements, information on paper production is presented here by printing method. The main categories are offset, gravure, flexography, and digital printing. Letterpress printing is of diminishing importance, and screen printing has a small but stable share in total printing. Because of their low importance, letterpress and screen printing are excluded from this study. *Table 7.1* shows the world shares of different printing technologies by values (Kettunen, 1999a, 1999b; US EPA, 1997).

Table 7.1. World shares of different technologies in the printing industry by value, in %.

	1994[a]	2000[b]	2010
Offset	47	42	33
Gravure	19	17	15
Flexo	17	19	20
Letterpress	11	6	4
Screen	3	3	3
Digital	3	13	25

[a]Based on US EPA (1997).
[b]The years 2000 and 2010 are based on Kettunen (1999a, 1999b).

The main production processes in printing are preprinting, plate making, printing, and finishing (Silferberg *et al.*,1998). In the finishing operation, a web of sheets is converted into the final product, such as magazines or books. *Figure 7.1* describes the printing process and environmental impact of the process steps (US EPA, 1997).

The pre-press processes include text processing and image processing. The data from computer is transferred by a network or a disk to an image setter in which images are formed as electronic data. The pre-press processes are often performed by special reproduction companies. Moving data directly from computer to film, called computer-to-film (CTF) technology, is widely used.

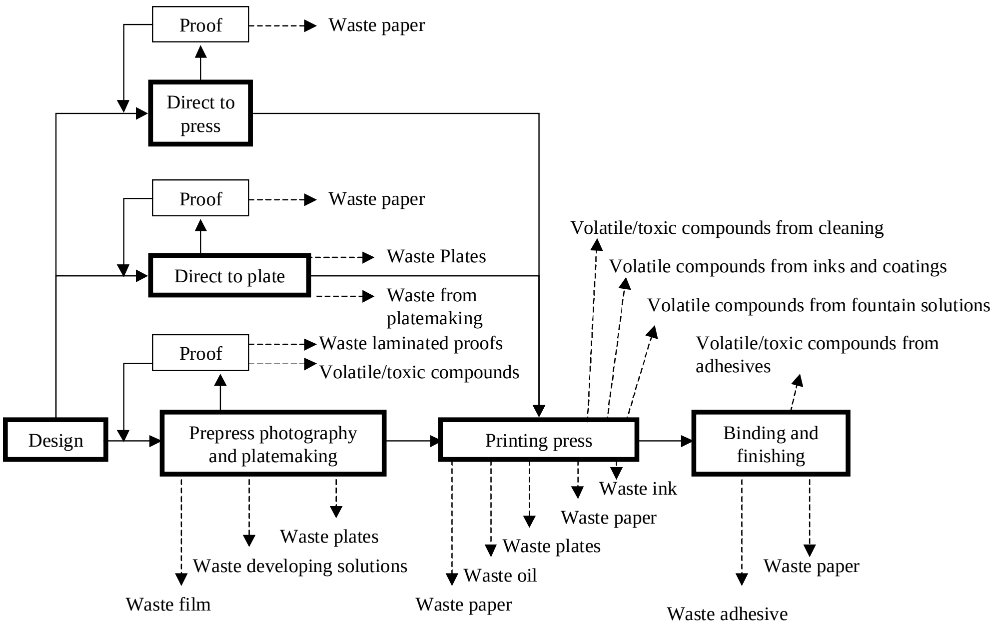

Figure 7.1. The printing process and its environmental impacts.

Printing forms transfer the printing ink onto the substrate. During production, the films are copied onto light-sensitive coating on the printing plates, which can be cylinders or screens. Before a printing form can be used for printing, it must be developed. Some printing methods require engraving or etching.

Computer-to-plate (CTP) technology makes it possible to produce printing forms directly from the computer without the photomechanical process. Offset printers are currently adopting this process, and it is assumed that it will become the dominant technology in the near future (US EPA, 1997).

After the printing form has been mounted on the press, the printing can be started. The printing methods listed above can be characterized by different ink carrying principles, ink compositions, and ink drying principles.

Ink normally contains four basic components: pigments, binders, solvents, and, additives. In general, pigments provide color, binders provide adhesion, solvents provide proper viscosity, and additives provide some optical and rheological properties. The pigments used are not those used in the paper industry, although titanium dioxide is to some extent used in both cluster branches.

When choosing between different printing methods, the main factors are printing speed, printing cost, printing substrate, and required printing quality. Offset is mainly used for magazines, books, newspapers, and advertising. Flexography is used for flexible packaging and corrugated board. Gravure is used for magazines, wallpaper, and flexible packaging. Gravure is slower than offset printing and requires long production runs in order to be cost efficient. The printing quality in gravure is high. Digital printing is efficient when small runs are needed.

In 1992, the average energy consumption in printing was 1.3 MWh/ton in Finland. The share of electrical energy was around 50% (Juntunen *et al*., 1994). When printing business forms, coldset offset printing consumes only 0.8 MWh/t due to penetration as a drying principle and high printing speed. In contrast, the flexography method consumes 1.7 MWh/t (Silferberg *et al*., 1998).

The average consumption of raw materials in Finland’s printing industry was 1.26 tons/ton of final product in 1992. The highest raw material consumption was in book printing and the lowest was in newspaper printing. Solid waste to landfills was around 3% of the production (Juntunen *et al*., 1994). In general, solid waste consists of empty containers, used film packages, outdated materials, damaged plates, developed film, dated materials, test production, bad printing or spoilage, damaged products, and scrap paper (US EPA, 1997).

Chemical discharges to sewage were 0.1–2.2 kg/ton and solvent discharges were 0.2–4.4 kg/ton (Juntunen *et al*., 1994). Wastewater from printing operations may contain lubricating oils, waste ink, cleanup solvents, photographic chemicals, acids, alkali, and plate coatings, as well as metals such as silver, iron, chromium, copper, and barium (US EPA, 1997). Freshwater consumption was around 3 m^3/ton (Juntunen *et al*., 1994).

VOC emissions from the EU’s printing industry are around 270 kton/year and are the principal environmental concern of that industry (Klimont *et al*., 1997). Emissions per ton are difficult to estimate. From the Finnish printing industry, consisting mainly of the printing of printing and writing papers, the VOC emissions are around 10 kg/ton (Juntunen *et al*., 1994). Packages naturally contain much less ink per ton of board. The different printing methods contribute to the VOC emissions from the EU’s printing industry as follows:

- Gravure and flexography for packaging, 59%
- Offset, 14%
- Gravure for publications, 16%
- Screen printing, 11% (Klimont *et al*., 1977)

VOCs originate mainly from solvents, which are used in inks, dampening, and cleaning. Alternative solvents may have a lower VOC content but still be toxic (US EPA, 1997).

Alcohol- and petroleum-based ink systems are major contributors to pollution. However, these solvents allow faster press speeds and longer printing cylinder wear, making them economically attractive (US EPA, 1997). Other possibilities are electron beam curable (EBC) inks, water-based inks, and waterless inks.

EBC inks consist of low-molecular-weight polymers that react with a stream of electrons from a vacuum tube. No solvents are needed. Because the curing only occurs after exposure to light, ink can remain in the ink fountain for long periods of time, reducing cleaning requirements. EBC dryers have high initial costs but low operating costs.

The proportion of organic compounds varies from 5–20% in water-based inks (*Atmospheric Emission Inventory Guidebook*, 1996). Water-based inks contain more chemical additives than do solvent-based inks. The use of those additives strongly influences print quality and generation of waste. The surface tension of water-based inks is high, resulting in reduced transfer efficiency of the ink. Compared with solvent-based inks, the drying energy requirement is higher and more operational difficulties can be involved.

The use of water-based inks affects recycled fiber pulping. Deinking material printed with water-based inks may be difficult. Switching from solvent-based inks to water-based inks may be costly at existing plants, and layout problems may occur due to the higher drying capacity required.

Waterless inks are highly viscous and have properties similar to those of solvent-based inks. Ink viscosity measuring systems control the viscosity of the inks to ensure quality and prevent the excessive use of solvent, thus reducing the potential pollution (US EPA, 1997). Waterless printing requires very careful control of the printing process and is only possible using special offset presses or refitted presses. Special plates, exposure methods, and plate handling techniques need to be employed when waterless inks are used. High capital investments are needed.

7.1.1 Offset printing

In the offset, or planographic printing method, ink is carried by a hydrofile substrate onto the printing plate. There are three main types of offset printing, each with a different ink drying principle: oxidation or ultra violet (UV) curing in the sheet-fed offset method, penetration into porous paper in the coldset offset method, and evaporation in the heatset offset printing method (Silferberg *et al*., 1998).

Offset printing is more environmentally sound than the gravure or flexography methods. The inks used are not usually solvent based. The main sources of VOCs are the alcohol added to the ink fountain solution and the solvent-based cleaning of the printing machine. Water consumption in offset printing is high. The sheet-fed offset method will probably become less important as a result of the growing share of digital printing.

There are several different types of plates used in offset printing, including photomechanical, electrostatic, bimetallic, relief, paper, and polymer plates. Photomechanical plates are the most common. In plate making, an image transparency is placed over the plate. The plate is then exposed to ultraviolet light, which hardens the coating. In developing, image areas are made receptive or repellent to ink. The uncured part of the light-sensitive plate coating is dissolved in the developer, increasing its hazardous nature; thus it should not be discharged to the sewage. A recent trend is the switch from solvent-based developers to water-based developers (US EPA, 1997; Silferberg *et al.*, 1998).

Laser exposure is used in CTP printing. Plates contain silver halides that must be processed as silver-containing films. Silver-free plates exist and are preferable from the environmental point of view. It is probable that in the future, developing will be done without the use of chemicals. This technique is used, for instance, in the computer to plate method in which silicon is removed from the plate by electrodes, sparks, or infrared laser diodes (Silferberg *et al*., 1998).

To work with water, a so-called fountain or dampening solution is emulsified into the ink. The purpose of dampening is to keep non-imaging areas of the printing plate free of ink. Isopropyl alcohol is commonly used in dampening.

To maintain image quality the intermediate blanket cylinder must be cleaned between printing runs. It is mainly ink and dust that are removed from the cylinder. The cleaning can be done manually or automatically (US EPA, 1997). Automatic washing systems use less cleaning agent and are preferred in new plants.

Cleaning of offset printing rolls led to 600–900 tons of petroleum-based VOC emissions in Sweden in 1994. This is a very high share (probably 10–20%) of the total VOC emissions from Sweden's printing industry. Easy-to-clean carbon-fiber-coated inking rollers have been introduced for the coldset offset printing method (Silferberg *et al*., 1998).

7.1.2 Flexography

In flexography, or relief, printing, ink is applied to an image raised above the non-printing layer. Evaporation is used for drying.

A printing plate made of rubber or plastic is used. Fast-drying inks make flexography an ideal method for flexible packaging, plastic, and foils. Soft rubber plate is also very suitable when printing on compressible substrates such as board.

Printing plates are made photomechanically. Plates are coated with solutions to make certain areas insoluble to water (US EPA, 1997).

Flexography and gravure are quite similar printing methods except for the printing plates and inks used (Hurst, 1995). Web-fed flexography and gravure are the primary sources of hazardous air emissions from the printing industry (The Air Pollution Consultant, 1995).

The primary VOC emissions in flexography come from plate making, ink drying, the laminating process, and cleaning of the printing equipment. Discharges to water consist of uncured resins from the printing plates and ingredients from water-based inks. Energy consumption for drying is relatively high when printing on non-absorbing substrates (Silferberg *et al*., 1998).

7.1.3 Gravure

In the gravure or intaglio printing method, ink is dosed into the small cups on the printing cylinder. Evaporation is used for drying.

Because of the costly printing plate cylinder, gravure is used for long runs, providing high quality at high press speeds. Cylinders are made of steel and plated with copper and a light-sensitive coating. Most cylinders are laser engraved. An excess amount of ink is applied to the cylinder. Small printing cups on the cylinder are filled by the ink and a doctor blade removes the excess ink before it reaches the substrate (US EPA, 1997). The two main types of gravure are publication gravure and packaging gravure. They do not differ considerably from each other in plate making but do differ in printing (Silferberg *et al*., 1998).

Solvent-, vegetable oil-, and water-based inks are available for gravure printing; the inks used are liquid (US EPA, 1997). Drying is the most critical phase. The main environmental concern from the printing stage is VOC emissions.

7.2 Best practices in the printing industry

From the environmental point of view, new printing techniques such as CTP and digital printing are the preferred techniques when a new printing plant is planned. Process steps including destroying chemicals can be eliminated.

The amount of waste can be reduced by carefully planned printing. For instance, using light colors prior to dark ones reduces cleaning requirements.

Using high-quality raw material lowers the amount of waste. This concerns the whole production chain, beginning at the pulp mill (US EPA, 1997).

7.2.1 Pre-press

Photo processing consists of developing, fixing, and washing (US EPA, 1997). The main environmental concerns are the emission of soluble complex silver compounds to wastewater and the large consumption of rinsing water used to flush the photographic films and paper in the developing and fixing process (Silferberg *et al*., 1998).

Developing solutions usually contain benzene deriatives. Powder-based developers are an alternative (US EPA, 1997). The lifetime of a developer can be extended using filtration and replacing worn-down components. Obsolete developers are treated externally. The COD content of developers is high.

Fixing solution contains 3,000–3,500 mg of silver per liter. Due to the high value of silver, almost 100% recovery, requiring subsequent recovery stages, is economically attractive. There are several methods for recovering silver used in the fixing process, including precipitation, electrolysis, metallic replacement, and ion exchange (US EPA, 1997; Silferberg *et al*., 1998).

The principle of hydroxide precipitation is to recover silver chemically. It is an efficient method, but the silver is not recovered in its pure form.

The principle of electrolysis is to use a controlled current in an anode–cathode array. The efficiency is lower than in precipitation. Electrolysis is usually combined with another technique.

In metallic replacement, the silver in the fixing solution is replaced with iron. This method has quite low costs, but is normally used only as a polishing step after electrolysis (US EPA, 1997).

Ion exchange units are more expensive and are mainly used only in larger printing plants. In this method, wastewater passes through a mixture of anionic exchange resins.

Consumption of rinsing water is high in the pre-press process. The concentration of dissolved silver in the rinsing water is in the range of 0.02–0.39 mg/l. Recovery of silver is often combined with efforts to reduce water consumption. Rinsing water can be recycled and reused, for example, in the mixing of fixing solution. The use of biocides, microfiltration, or UV radiation to prevent the growth of microorganisms is required for recycling rinsing water. To achieve higher rinsing water reduction rates, silver recovery facilities must be installed. The investment cost for recycling 100% of the water is low; a figure as low as 13,000 ECU has been reported for one Danish printing plant.

One American company reduced its wastewater by over 99% and its other waste by 93% by closing the water circulation. Ion exchange and filtering are used to clean the rinsing water. Electrolysis and ion exchange are used to remove silver from the spent fixing solution. Together with the waters from the printing operation, the excess water is collected and evaporated. The investment costs were 35,000 ECU; with a payback time of only 1.6 years.

Solvents should be used in cleaning only when necessary. Recycling them is recommended from both the environmental and the economic points of view. When short print runs are used, more VOCs are usually released from evaporating press cleaners than from the inks themselves. Installing an on-site solvent distillation unit for solvent recovery can extend the lifetime of the solvent.

The silver-recovery process can be avoided by using photopolymer films. Another alternative is to use electrostatic films (US EPA, 1997).

7.2.2 Offset printing

Machines for automatic development of plates introduce the possibility of recycling and filtering the solution. Consumption of developers can be decreased, and rinsing water used in plate production can be partially recycled. A 75–90% reduction in rinsing water consumption is possible when it is cleaned and reused.

If solvent-based inks are used in offset printing, the environmental impact of the printing process is not very different from when solvent-free inks are used. In the coldset offset method, up to 95% of VOCs from the inks stay in the product, transferring the problem to the deinking facility. In the heatset offset method, the corresponding figure is 60%.

Vegetable oil-based inks containing soybean oil can theoretically reduce the VOC content by 80%. However, such inks can replace only 40% of the ink used if petroleum-based inks are used. Moreover, they are more expensive than other inks.

Paper recycling transfers the environmental problems of the printed product to the papermaker. Because of the high boiling point of solvent-based inks in offset printing, those inks do not emit VOCs, however, vegetable-oil-based ink sludge generated during deinking is more biodegradable than solvent-based inks. On the other hand, especially in the coldset offset method, the vegetable-oil-based inks have a tendency to cling tightly to the fibers, making deinking more difficult. Heavy-metal-containing inks should not be used (Silferberg *et al.*, 1998).

An ink recovery system can be economically very attractive. One American printing company saved 2% of turnover in ink disposal costs and ink purchases per year after introducing an ink reclamation system (US EPA, 1997). In high-quality printing, the reuse of inks cannot be very extensive. Usually, all of the recovered inks can be used in the production of black ink.

The main component in the fountain solution is water, but the use of isopropyl alcohols in concentrations of 4–15% results in significant VOC emissions. Only in coldset offset printing is alcohol not normally used. The problems related to the use of a large amount of alcohol can be avoided or reduced by replacing alcohol with, for example, glycol ethers or by using waterless offset printing. An isopropyl alcohol concentration of 5% is possible without jeopardizing the printing quality. Waterless printing is not considered economically attractive.

Glycol ethers are an example of substitutes for isopropyl alcohol. Like alcohol, these substitutes reduce the surface tension of the fountain solution. The problem is that the concentration of glycol ether must be exactly right, otherwise the conductivity of the water causes problems. An automatic fountain mixing system automatically mixes the fountain concentration to the correct concentration. Other problems with substitutes are foaming and evaporation, with the latter changing the critical concentration of the fountain solution. A foam-free system and refrigeration are preventive measures (US EPA, 1997).

Installing a continuous dampening system is one way to decrease the use of VOC-emitting isopropyl alcohol in the dampening mixture. It is normally added using an intermittent-feed system. Softer rubber dosing rollers are recommended because they are more water receptive. Ceramic transfer rollers have good water-holding capacity and they facilitate the transfer of dampening solution. By using a rubber metering roller and ceramic transfer rollers, the isopropyl alcohol content in the fountain solution can be reduced to levels as low as 4%. With a reverse slip nip, where both rollers at the metering contact travel in the same direction, the use of isopropyl alcohol can be eliminated. Another possibility for reducing the use of isopropyl alcohol is to replace roll application of the fountain solution with spraying (Silferberg *et al.*, 1998). Replacement of dampening and dosing rollers is estimated to cost only 10,000–20,000 ECU (Intergraf/EGF, 1999).

The hazardous liquid in offset printing can be reduced by 50% by replacing alcohol in the dampening system. One American company saved around 36,000 ECU in disposal costs annually, accounting for 0.25% of turnover, by replacing isopropyl alcohol (US EPA, 1997). Savings of this kind make the payback periods of dampening development investments very short.

Another American printing company with a turnover of 25 million ECU using a normal 15% isopropyl-alcohol-containing fountain solution installed a system that replaced the use of isopropyl alcohol at a cost of 100,000 ECU. Recharging of the solution is controlled by computer. Reverse osmosis is used to clean the used solution. A payback period of only 30 months is required (US EPA, 1997).

The hardness of the water used in printing must be correct to prevent waste and poor printing quality. Using filtering, softening, reverse osmosis, and hardness balancing, it is possible to achieve the proper hardness for printing. Controlling the hardness level is even more important when using isopropyl substitutes. Low nip pressures and soft rolls are preferred.

In sheet-fed offset printing water-based overprint varnishes are probably the best option from the environmental point of view. Mineral-oil-based and vegetable-oil-based varnishes are available with the same benefits and drawbacks as in the case of inks. UV-curing ink and varnishes are alternatives that do not emit any organic compounds. Drying UV-curable coatings and inks and water-based coatings is very energy consuming. UV-curing equipment is considered to be cheaper than interactive techniques for small headset offset printers (Intergraf/ EGF, 1999).

Vegetable-oil-based cleaning agents are available. However, their use in coldset and heatset offset printing is limited because of the drawbacks of the process. Another alternative is to use high boiling temperature solvents. With these solvents, the evaporation temperature is high, and results in low VOC emissions. Toxicity, however, is a problem with such solvents.

The lifetime of a washing solvent can be extended by using, for instance, a cyclone-type filter (US EPA, 1997). Used cleaning agents must be handled as chemical waste.

Heatset offset printing has some negative effects on the environment. Warming the drying air consumes a substantial amount of thermal energy. Other concerns are exhaust gases from the drying ink and the inefficiency of the cooling system.

Drying energy can be saved by

- using inks with less solvents
- decreasing gas consumption by minimizing air flow
- using exhaust gas energy to warm input air
- minimizing the ink used by using achromatic color separation
- using the recovery systems of energy

In heatset offset printing, encapsulation and ventilation should be used to direct emissions to the afterburner. Exhaust gases contain VOCs from inks, isopropyl alcohol, and cleaning agents. Thermal and catalytic systems are used to eliminate VOC emissions. Afterburners are discussed in Section 9.

7.2.3 Flexography

Engraved metal plates have been replaced by photopolymer and rubber plates, which can be engraved using a laser. The latter method, used in CTP technology, requires no chemicals (US EPA, 1997).

Printing plates are usually developed using volatile organic solvents. Several solvents exist, all with different environmental impacts. The plate-making device is normally closed, but certain amounts of vapor are emitted. VOC-containing liquid is enriched by dissolved photopolymer resin from the plates. The liquid is recovered by vacuum distillation and reused. The sludge should be treated as hazardous waste. The use of water in developing is possible but drawbacks in printing have been reported (Silferberg *et al*., 1998; US EPA, 1997).

Flexography printers, especially corrugated container printers, have widely adopted the use of water-based inks. A problem with such inks is the longer drying time, leading to investments that are not necessarily economically attractive at existing plants. By using ceramic anilox cylinders, the problem with the high surface tension of water-based inks, and hence problems with the transfer of ink, can be avoided. Improved doctor blade technology improves ink transfer and reduces vaporized ink. A new class of water-dispersible, faster-drying neutralizing resins have been introduced for water-based inks and overprint varnishes, decreasing the use of traditional neutralizing chemicals that cause VOC emissions. It is important to control the pH level of the solution when moving to water-based inks.

Water-based inks contain significantly fewer VOCs than do solvent-based inks. In one American printing plant, 21% of the solvent-based inks were replaced with water-based inks resulting in 72% fewer VOCs. For this change, the drying capacity was increased, the press roll was modified, and ink handling was upgraded. The savings in the waste treatment resulted in a payback period of 2.5 years. In another plant, VOCs were reduced by 88% when water-based inks were introduced. In this plant, the costs of adopting water-based inks were over 2.5 million ECU; therefore, a short payback period is not expected. When solvent-based inks are replaced with water-based inks, significant savings in addition to those from reduced disposal costs can be obtained from reductions in fire insurance premiums (US EPA. 1997).

UV curing inks are used when printing labels and small carton boxes (Silferberg *et al*., 1998). UV curing in flexographic printing provides good resistive properties and economical curing. UV curing inks contain low amounts of VOCs and require less cleaning. On the other hand, such inks can lead to problems concerning product quality, deinking, capital investments, and higher energy requirements (US EPA, 1997; Silferberg *et al.*, 1998). UV curing inks contain some skin-irritating compounds (Silferberg *et al*., 1998). Switching to UV curing inks may not be economically attractive in existing plants.

Water-based and natural-solvent-based inks contain variable amounts of solvents. Solvents from the exhaust air can be recovered. Afterburners and recovery techniques for solvents are discussed in Section 9.

Distillation can be used to recover solvents from the spent mixture of ink and solvents. Flexography is characterized by a large amount of ink waste. For one American printer, installing a distillation unit to recover solvents for markets and to reduce the cost of off-site shipments of hazardous waste required only a 20,000 ECU investment and led to annual savings of 120,000 ECU. Another possibility is to reuse solvents in cleaning.

Installing pumps, piping, valving, and computer hardware to automate ink and solvent mixing resulted in a 16% reduction of ink-laden solvents, a 57% reduction of evaporated solvents, and a 75% reduction of evaporated alcohol in one American printing plant. The plant’s annual savings were 85,000 ECU from an investment of 280,000 ECU, leading to a payback time of 3.2 years (Hurst, 1995).

When using the Chamber doctor blade inking system, less ink is needed and the runnability of the machine is improved. This technology should be adopted in new plants. The hot drying air must be recovered and recycled.

In the case of flexible packaging, laminates, which contain at least the same amount of adhesives as ink, are used. Solvent-free two-component adhesives can be used, but only in new plants.

The printing plates, inking system, etc., are cleaned using solvents if solvent-based inks are used. If water-based inks are used, water can be used for cleaning. Baking powder is another alternative. Easy-to-clean presses and pumps are available and should be used in new plants. One example is the Teflon-coated press. If water-based inks are used, cleaning is more important.

The rinsing water from the different cleaning operations and wastewater from production of water-washable printing plates should be treated in the production plant and reused if possible; the sludge should be taken care of as hazardous waste (Silferberg *et al*., 1998). Wastewater treatment and sludge drying by using natural gas resulted in a 54% reduction of waste in one American printing plant. Net annual savings in disposal costs were 27,000 ECU versus an implementation cost of 40,000 ECU.

Wastewater from using water-based inks can be processed using, for example, chemical precipitation or ultrafiltration. The ultrafiltration technique, presented for the case of papermaking in Section 4, is used for cleaning the effluents from the coating of the paper. The payback times are usually relatively short. Inks can be ordered with a higher content of dry solids and the wastewater can be used in the fountain (US EPA, 1997).

7.2.4 Gravure

Copper and chromium plating of gravure cylinders result in metals that should be taken care of. Polishing operations also generate chromic air emissions. Engraving is preferred to etching because of the environmental problems associated with etching chemicals. Moreover, etching requires the use of photographic films and chemicals in the pre-press processes. New printing cylinder manufacturing techniques should be adopted in new plants.

Different systems for processing cylinders include the Ballard skin, dechroming, grinding, and cylinder surface recycling. If the Ballard skin is made on the cylinder surface, separation layers containing silver or mercury should not be used.

When cylinders removed from the different electrolytic baths are rinsed, the rinsing water should be recycled. Chromium vapors from the electroplating bath must be collected, condensed, and discharged as hazardous waste. All used solutions from cylinder preparation must be treated as hazardous waste (Silferberg *et al*., 1998).

The amount of ink used can be reduced by using modern doctor blade technology. Installing that technology in new plants is highly recommended.

Ink kitchens automatically mix inks to the correct color and thus reduce waste. The payback period for automatic ink-mixing equipment was 6 years in one American printing plant.

Gravure presses normally use heatset inks, which are set by exposure to heat in an oven. Heatset inks are usually solvent based because of the high drying capacity required. Printing machines using solvent-based inks run faster, mainly because of the inks' shorter drying time. Vegetable-oil-based inks are also available; they provide good printing results but the drying speed is slower (US EPA, 1997). Higher drying capacity or lower machine speed result in additional costs. Water-based inks are also available, with problems similar to those of vegetable-oil-based inks. Using the gravure method with water-based inks causes problems with uncoated paper due to direct contact with fibers.

When the gravure method is used for printing packages, the inks have to suit several substrates. Inks more like those used in flexography are usually used. Solvent-based inks provide good quality and efficiency. Solvent abatement technologies are discussed in Section 9.

Cleaning should be done with water and baking powder instead of solvents, and machinery should be closed for cleaning (Silferberg *et al*., 1998). Considerable annual savings can be achieved by using recovered solvents for cleaning. Waste reductions of over 30% as a result of partial reuse of ink and solvents are realistic (US EPA, 1997).

7.3 Other environmental issues

Digital printing is the fastest-growing printing technology. The environmental impact of the technology is minor. The technology does not include film processing or plate making. Heat fixation is used to set the ink. Compared with traditional printing methods, the waste generation with this method is modest. Digital printing has a significant share in new printing machine investments; in particular, it has reduced new investments in the sheet-fed offset technique.

The main environmental concern in coating the printed product is the emission of solvents when using solvent-based lacquers. If possible, coating of printed paper and board should be performed without such lacquers. Water-based dispersion lacquers or UV-curing varnishes are available, but they have the disadvantage of leading to higher energy consumption. If solvent-based coatings are used, incineration techniques for destroying VOCs can be used. These techniques are discussed in Section 9.

The adhesives normally used in binding are water based. However, they cause problems with deinking. Using the wire-stitching technique can eliminate this disadvantage (Silferberg *et al.*, 1998).

The packaging industry converts a web of board into boxes of different shapes. It is a large industry, but its environmental impact is minor[3]. Making transport packaging from fluting and liner consumes approximately 0.15 MWh/ton of electricity and 0.5 MWh/t of heat. Starch is used in gluing. Consumption of starch is on average 25 kg/ton (Lahti-Nuuttila, 1998). The amount of reject in packaging material conversion plants is relatively high, making it probably to the most important environmental factor to be improved. Recycling, incineration, and landfilling are the disposal alternatives available. The raw materials used influence the recycling and incineration possibilities. VOC emissions originate mainly from printing. Solvent-based glues and silicones are usually used, but water-based replacements are available (UPM-Kymmene, 1998). The development of lean material packaging solutions is the most important environmental area to which packaging industry can contribute.

[3] Conclusion drawn from the environmental reports of several packaging industry companies.

8. Wood furniture production and wood preservation

8.1 Wood furniture production and its environmental impact

The environmental impact of wood furniture production arises chiefly from wood coating. In the EU, prior to the membership of Finland, Sweden, and Austria, the value of industrial wood coating was approximately 1,000 million ECU, with furniture production having a 70-80% share (Giddings *et al*., 1991).

The wood furniture industry is characterized by low-end products made of fiberboard with a less labor-intensive finishing process and high-end products made of solid wood with multiple labor-intensive finishing steps. The latter group consumes the largest share of coatings (The Air Pollution Consultant, 1996). The coating of luxury wood furniture is critical for product's aesthetics and can involve extensive application processes. In low-end wood products, the coatings are mainly used for protection (Anex and Lund, 1999).

The coating types include standard polyurethane, nitrocellulose, acid-catalyzed, polyester, UV curing, and water-borne coating. The four basic constituents of liquid coatings are a liquid solvent, a binder, pigments, and additives. Varnishes and lacquers do not contain any pigments. The application method, application conditions, appearance of the final product, and technical specifications determine the composition used (Giddings *et al*., 1991).

The primary input for wood furniture is lumber. The production process includes steps such as drying, sawing, planing, sanding, gluing, and finishing. *Figure 8.1* illustrates the wood furniture manufacturing process and its emissions (US EPA, 1995).

Drying of sawn timber is performed if a company does not purchase already dried sawn timber. A drying kiln or oven is used. Waste wood is burned.

The types of power saws used in furniture manufacturing include circular saws, band saws, scroll saws, radial saws, and portable hand saws. The primary outputs from sawing and planing are wood chips.

Bending of wood is performed using softening agents such as water and pressure. After bending, the wood is dried. The same drying methods are used as are used to dry sawn timber.

The assembling and finishing stages can be performed in either order. Assembly is carried out first if curved and irregular components are included. Polyvinyl acetates are commonly used as adhesives during assembly. Solvents containing formaldehydes are used for upholstered furniture. Veneer is applied after assembly. Adhesives are used and some solvents are released during the process.

Sanding smoothes the surface for the finishing stage. The primary outputs are wood particles. After initial sanding, an even smoother surface is achieved by spraying, sponging, and dipping the furniture part with water, which causes the fibers of wood to swell. After drying, a solution of resin or glue is applied. The raised fibers become more brittle. The part is sanded again to eliminate the raised fibers. The primary byproducts are wood particles, glue, and resin.

For some purposes the wood is bleached. Hydrogen peroxide is normally used (US EPA, 1995). Sometimes derosination is carried out before bleaching if the resin causes problems. Solvents are used in that process.

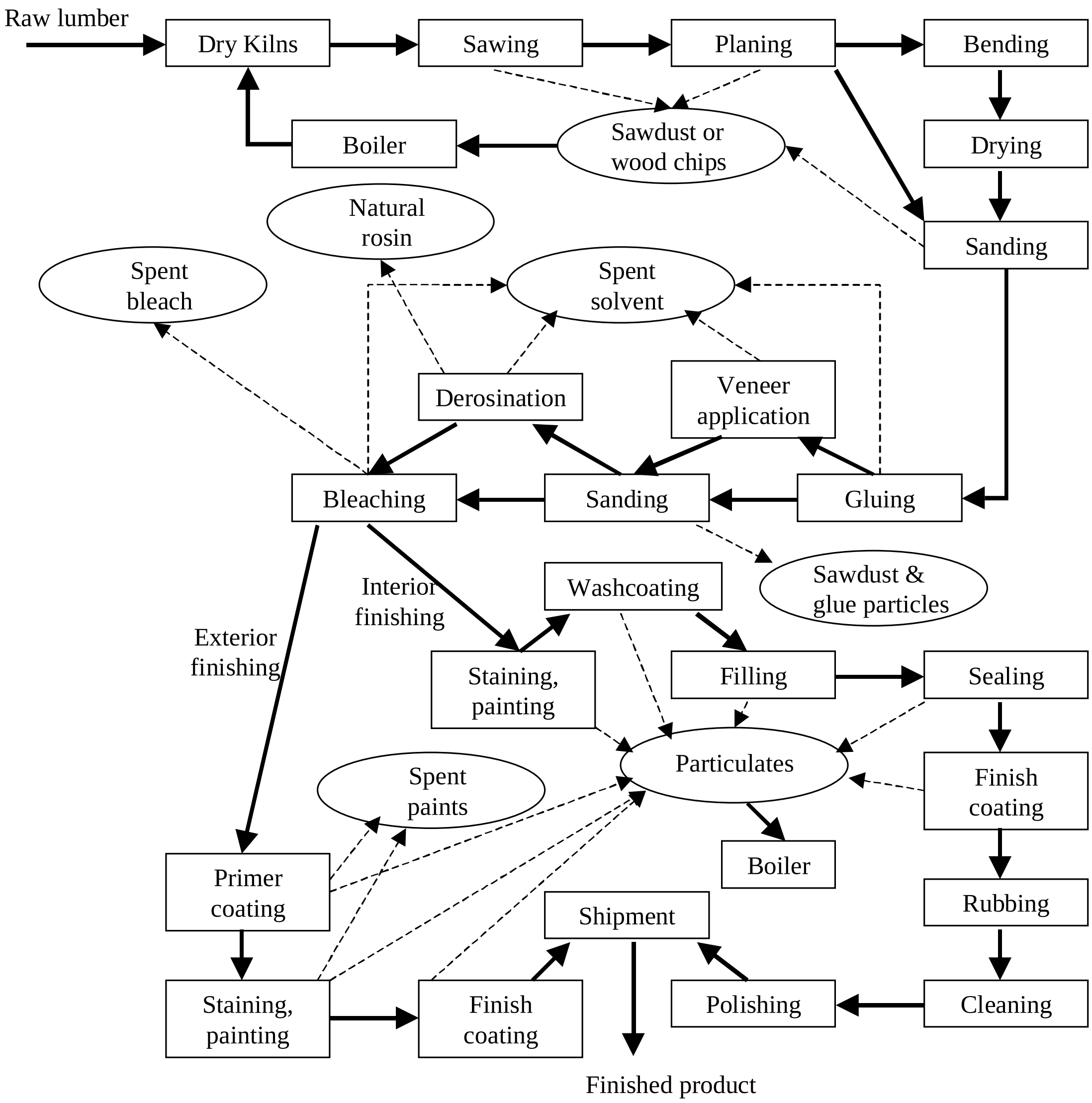

Figure 8.1. Wood furniture manufacturing process.

The main surface coatings are paints, varnishes, and lacquers. The factors determining the method of application are the nature of the wood surface, the geometric design of the work, the specifications for quality and allowable costs, the production quantity and rate, the requirements for surface preparation, and the end use of the product (UN 1983). Roll coating and curtain coating are the principle methods for flatline finishing (US EPA, 1995). Spraying and dipping are other options if finishing is done after assembly. In addition to solvent-based coatings, coatings with a higher content of dry solids, water-based coatings, coating powders, and low-reactivity solvent-based coatings are available (Giddings *et al*., 1991).

Staining is the application of a color that does not hide the original wood grain. Solvents and VOC-containing compounds are used. A washcoat after staining is used to aid in adhesion, assist in achieving color uniformity, and prepare the wood for another sanding after stain application. Nitrocellulose-containing washcoats are usually used.

Fillers are applied to the wood surface to produce a smooth, uniform surface for the later stages of the finishing process. Fillers contain VOCs. After the filler is applied, the surface is sealed for adhesion, to make sanding more effective, and to prepare the wood for further coating applications. Sealing is usually done with nitrocellulose-based lacquers. After sealing, rubbing, polishing, and cleaning are the final steps.

Priming is performed for outdoor furniture to repel moisture. Staining or painting is the next step. Varnish is applied to protect the color (US EPA, 1995).

Coatings are dried using evaporation, chemical reaction, or radiation curing. The resin system used determines the method of curing (Giddings *et al*., 1991).

The most important environmental impact from wood furniture production is emissions to the air from the solvent-intensive finishing operations (US EPA, 1995). High-pressure spraying in spraying booths generates the highest solvent emissions (Johansson *et al*., 1984). Typical outputs from the pre-finishing steps are the solvents used in derosination and spent bleaching agents.

The devices most commonly used to reduce particulate matter emissions from wood-fired boilers are mechanical collectors, wet scrubbers, electrostatic precipitators, and fabric filters. The techniques used are the same in all the forest cluster branches. The last two techniques are used when efficiencies over 95% are required.

Coatings are usually applied in spray booths. Dry filters are used to control particulate emissions. It is possible to recycle a portion of the exhaust from the spray booth.

Solvent-based nitrocellulose lacquers are the coatings used most often in wood furniture manufacturing. Industrial solvents are used predominantly for cleaning application equipment. Cleanup solvent is usually reused and eventually disposed of (US EPA, 1995). Distillation, condensing, adsorption, and absorption are the solvent recovery methods used (Johansson *et al*., 1984).

Thermal incineration is the abatement technique most often used when concentrations of aliphatic and aromatic hydrocarbon and oxygenated hydrocarbon solvents are high. The potential for adsorption increases when concentrations are lower or solvents from air-drying are treated. The feasibility of using biofilters depends on the space available for their installation (Giddings *et al*., 1991). Abatement technologies are discussed in Section 9.

The use of a water wash spray booth and water scrubbing of ventilated air generates wastewater containing some volatile and toxic chemicals. Wastewater is also generated by spills, washing, and raw material production. Distillation, incineration, and settling tanks, ponds, and basins are used for treatment. Other methods are expensive (UN, 1983). Coating sludge is sent to special landfills. Sludge treatment systems exist that generate dry powder from the paint sludge that is usable in various industries as fillers (Giddings *et al*., 1991).

The environmental impact of the wood furniture industry is noticeable only with respect to VOC emissions. In the EU, solvent emissions from wood furniture coating (excluding emission figures for Finland, Sweden, and Austria) were approximately 0.25 million tons in 1991. Compared with emissions from the other cluster branches, all other emissions from the wood furniture industry are minor. Only particulate matter emissions have a small share of the forest cluster's total particulate matter emissions (US EPA, 1995). In Europe there are country-based maximum emission reduction levels for wood furniture coating operations. These are different for each coating type. If solvent-based coatings are used, some kind of abatement technology is always needed to meet the requirements (Giddings *et al*., 1991).

8.2 Best practices in the wood furniture industry

Pollution prevention opportunities in the wood furniture industry fall into the following groups:

- Production planning and sequencing
- Process or equipment modification
- Raw material substitution or elimination
- Loss prevention and housekeeping
- Waste segregation and separation
- Solvent recycling
- Training and supervision

As in the printing industry, applying lighter shades prior to darker shades when staining or painting reduces cleaning requirements. Another option is to apply one color batch, reducing the cleaning requirement further.

The assembly step is not a major source of emissions. There are, however, some options for reducing VOCs. Hot melts and polyvinyl acetates do not contain VOCs and could be used instead of adhesives containing VOCs.

The coating should not be applied using a sprayer (US EPA, 1995). If spraying is required, one option is to move from conventional spraying to high-volume low-pressure spraying, which results in lower overspray and lower VOC emissions (Giddings *et al.*, 1991). Another option is to move toward coating of wooden panels, or flatline finishing, rather than spraying the finished product. This enables the use of more efficient application techniques (UN, 1983). With respect to minimizing excess coating, roller and curtain coating methods are more efficient than spray coating (Giddings *et al.*, 1991).

It is possible to recover and reuse overspray, for example, as a sealant. The amount of VOCs emitted during spraying are not reduced, but at least emissions to water and disposal costs are reduced (Kranz *et al.*, 1997). Use of water wash spray booths decreases the emissions from cleaning, but wastewater can be a problem (UN, 1983).

Because of the annual savings in coating costs, high-volume low-pressure coating and flatline finishing lead to positive net present value and payback periods of 1–2 years; they can therefore be referred to as best practices. Flatline finishing can reduce VOC emissions by as much as 25% (US EPA, 1995).

Coating and curing processes should be done in a closed environment. Directing the effluent gas stream to the abatement equipment can decrease emissions considerably (Giddings *et al.*, 1991).

Up to an 80% reduction in exhaust air is possible if the spray booth uses air curtains. Partial recirculation of exhaust air in the spray booth is also possible (US EPA, 1995). The mobile zone spray booth is an emerging technology that reduces VOC emissions by eliminating emissions during the transportation of furniture to subsequent steps in the process (The Air Pollution Consultant, 1996).

Like UV and infrared curing, radiation curing does not require solvents. Roller coating is the only available application method. Wetting of wood is a potential problem that restricts the use of radiation curing (Giddings *et al.*, 1991). UV curing is only practical in flatline coating operations. The location of UV lamps may be a problem if cases are coated (US EPA, 1995). UV systems are costly but efficient. Energy consumption is lower than with conventional drying. However, some colors and glosses are difficult to achieve. If UV-cured coatings are used, the coating formulations for tabletops may still be solvent-based because of the high quality requirements.

Water-based coatings are better than solvent-based coatings with respect to air pollution and toxicity, but they are more sensitive to contamination and to variations in humidity and temperature. Switching from solvent-based to water-based coatings can lead to a lower production rate. Water-based coatings require more drying capacity. Moreover, water-based coatings still contain some VOCs. The costs of retrofitting an existing plant for water-based finishes range between 300,000 and 500,000 ECU per facility because stainless steel must be used.

The same application methods used for solvent-based coatings can be used with water-based coatings (Giddings *et al.*, 1991). However, darker wood sometimes appears cloudy when finished with a water-based coating. (UN, 1983). Water-borne finishes do not have the rubbing capacity of nitrocellulose lacquers, and should not be used if a glossy finish is required. On the other hand, water-based coatings are considered more suitable than solvent-based ones for finishing open-pore woods (US EPA, 1995).

In one American wood furniture coating plant, a water-borne system led to problems such as upstanding wood grains, yellowing of stains after exposure to sunlight, and inconsistencies in stain quality. The net present value of the switch to a water-based system was, however, positive (Kranz *et al.*, 1997).

Coatings with a dry solids content of 80% or more are available; generally, all the application methods described above can be used with such coatings. Coating powder, for example, is VOC free. Overspray material can be reused and hence waste production is minimal. The difference in appearance is, however, quite significant. Not all colors can be reproduced (Giddings *et al.*, 1991).

Polyurethane coatings are available and can be applied using many methods. The coating result is always glossy. Polyurethane coatings require a clean room and imperfect coating is difficult to repair (US EPA, 1995).

Segregating the spent solvents by solvent type makes recycling possible. For instance, isopropyl acetate generated during cleaning can be distilled. Net present values of recovery and recycling techniques are positive and payback periods are 1–2 years. These techniques can be considered best practices (US EPA, 1995). Best practices in abatement techniques are discussed in Section 9.

8.3 Wood preservation

Preservatives are applied to wood to achieve a longer lifetime for wood typically used outdoor. Wood is preserved to protect it against fungal and insect attack and against weathering. Products include telegraph poles, railway sleepers, and construction materials. Around 6 million m^3 of timber were preserved annually in the EU before the membership of Finland, Sweden, and Austria. There are around 1,000 wood-impregnation sites in the EU, thus the average size of these businesses is small. Creosote, organic solvents, and water-borne preservatives exist. VOC emissions from the preservation of wood were 136,000 tons in Europe in the mid-1990s (Klimont et al., 1997). Wood preservation accounted for 0.8% of total VOC emissions in Europe in the mid-1990s.

Two drying methods, air seasoning and kiln drying, are used for applying water-based preservatives after debarking. Steam vacuum drying is primarily used for creosote. In that method, the wood undergoes a pressurized steam treatment, and a vacuum is then used to remove excess moisture from the wood (UN, 1983).

Creosote is oil prepared from coal tar distillation. VOCs make up approximately 10% of the creosote used for wood preservation. Creosote is used for wood destined for outdoor uses, such as for telegraph poles and railway sleepers (Giddings *et al.*, 1991). The lifetime of creosote-impregnated poles is 40–70 years (Metsäliitto, 1999). In most applications, creosote can be replaced with water-borne preservatives.

Water-based preservatives consist of solutions of salts in water (Giddings *et al.*, 1991). The lifetime of salt-impregnated poles is 30–70 years (Metsäliitto, 1999). Water-based treatments are popular for applications where it is necessary to paint the wood after treatment or where odors from creosote treatment are unacceptable (UN, 1983).

Solvent-based preservatives are used predominantly in the construction industry. These preservatives have the advantage of keeping very precise dimensions of the wood intact. Introducing water-based preservatives into an existing plant may be costly because of the stainless-steel requirements. Another advantage compared with water-borne preservatives is the faster drying time.

In 1991, water-based solutions accounted for 13% of total preservative consumption in the EU. The share of creosote consumption was 54% and that of solvent-borne solutions was 33% (Giddings *et al*., 1991). Preservatives can be applied by using vacuum processes, dipping, spraying, or brushing. The efficiency of spraying is only 10%, that of the other applications is around 90%.

In the vacuum process for creosote application, timber enters a chamber that can be pressurized with air. The chamber is flooded with hot creosote for 1–3 hours. After draining, a vacuum is applied to draw off the excess creosote. The timber is then left to dry in the open air. Water-borne preservatives are applied in the same way.

In the vacuum process for organic solvent application, timber is placed in a chamber, which is subsequently evacuated. The chamber is flooded with preservative and pressurized for 5–20 minutes. After draining the chamber, a final vacuum is used to draw off the excess preservative. The timber is left to dry in the open air.

A thermal treatment process is also available but is not widely used. The VOC emissions from this process are considerable. Capturing these vapors and condensing and returning them to the tanks is the only control alternative (UN, 1983).

Pressure treatment leads to VOC emissions, mainly from the drying of impregnated wood and to a smaller extent from preparation and handling. Drying is usually performed in the open air (Klimont *et al.,* 1997). Emissions can be reduced through proper solvent management, by enclosing the process wherever possible so that air can be extracted through abatement equipment, and by using alternative low-solvent coatings where possible (*Atmospheric Emission Inventory Guidebook*, 1996).

The primary water pollutants are condensate and condensed vapors from the conditioning and treatment processes. The amount of effluents is, however, small. The three primary steps for the treatment of wastewater contaminated by oil-borne preservatives are as follows:

- Primary separation of free oil and solids
- Removal of emulsified oil and suspended solids
- Removal of dissolved organic compounds (UN, 1983)

Gravity separation, dissolved air flotation (as in papermaking), and granular media filtration are the alternatives for the first step. Free creosote can be recovered.

In the second step, emulsion is broken by coagulation or heating. Sedimentation, dissolved air flotation, and granular media filtration are then used.

Biological treatment is usually performed in the last step. Waste stabilization ponds and activated sludge treatment are used. Waste stabilization ponds do not require high capital investments and are inexpensive to operate. However, they do require warm temperatures the whole year. It has been estimated that even by performing only the first step, over 80% of CODs can be removed at relatively low annual costs. Introducing the other steps results in considerably higher costs.

If water-borne preservatives are used, chemical reduction and oxidation reactions followed by precipitation or filtration are used to remove different metals. Lime is added to neutralize acidic wastewaters. Ion exchange and precipitation can be used to remove some metals. The costs of those measures are not high (UN, 1983).

Part of the emissions may be fugitive emissions and hence abatement techniques can capture only a part of the total emissions. (Klimont *et al*., 1997). Fugitive emissions occur throughout the handling, application, and drying stages of the processes. Timber impregnation using the closed double vacuum process minimizes fugitive loss. It has been estimated that the closed double vacuum process can decrease VOCs by 40%.

Activated carbon adsorption and incineration can be used as an abatement technology. Those techniques are discussed in Section 9. Because of fugitive emissions, the efficiency estimation for those techniques is only 60% (Klimont *et al*., 1997). The cost of double vaccum impregnation is about half that of activated carbon adsorption. The cost is still relatively high for existing plants (Klimont *et al*., 1997).

Emissions from burning creosote-impregnated wood do not differ much from those from non-impregnated wood, provided a high incineration temperature is used (Metsäliitto, 1999).

9. VOC abatement technologies of in the mechanical forest industry and the printing, wood preservation, and wood furniture industries

External abatement techniques to reduce VOC emissions are used if internal measures to reduce emissions are not sufficient. Otherwise, the environmental efficiency of those techniques is too low to be attractive. The cost of the abatement technologies is usually acceptable only at those sites having economies of scale for installing an abatement device.

Abatement techniques are approximately the same for printing plants, wood coating plants, and wood preservation plants, as well as for some wood panel manufacturing plants. The most suitable abatement technique depends on the gas flow rate, the reduction efficiency required, the space available, opportunities for heat recovery, waste disposal, and effluent treatment facilities (Giddings *et al*., 1991). The techniques used include incineration, adsorption, condensation, and biofiltering.

Thermal and catalytic incineration techniques are used. The basic types are line burner, tunnel incinerator, and jet incinerator. It is possible to integrate a heat recovery system into this kind of system. The stages in incineration are burning, mixing, and afterburning. In the afterburner, the hot gas from the burning stage and contaminated air are held at the temperature generated by the burner. Modern pretreatment facilities reduce the fuel required.

Recuperative and regenerative heat recovery systems are available in thermal incineration. The former is more suitable for low flow rates and high VOC concentrations and the latter is preferable for high flow rates and low VOC concentrations. If there is a kiln or boiler on site, it can be used for incineration of VOCs, as is often done in wood panel plants.

Combustion generates CO, NO_x and other pollutants. NO_x emissions from recuperative combustion can be significant: one printing plant emitted 32 tons in a single year, which is on par with NO_x emissions from pulp and paper production per ton. NO_x emissions from regenerative combustion are minor. The cleaning efficiency in thermal combustion is 99%.

The principle of catalytic incineration is that oxidation of VOCs takes place on the catalyst's surface versus in the air. The operating temperatures are lower than in thermal afterburners and hence fuel consumption and NO_x emissions are lower. The catalyst bed must be replaced every 2–5 years (Giddings *et al*., 1991). The combustion temperature in the catalytic afterburner is less than half of that in the thermal afterburner. Energy consumption is therefore lower. Cleaning efficiency in catalytic combustion is 95%.

In other abatement techniques VOCs are recovered, not destroyed. Adsorption is one such technique; the activated carbon method is the most common. VOCs at concentrations lower than those in incineration can be treated. The disadvantage is that when more than one solvent is used, their reuse after adsorption is impossible. The adsorption bed must be regenerated. The efficiency of the technique after regeneration is almost 100%, but it decreases gradually (Johansson *et al*., 1984). The biofilter technique is also an alternative if the concentration of VOCs is low (Giddings *et al*., 1991).

Adsorption with activated carbon is possible except where alcohol and acetate solvents are used. The activated carbon method has been estimated to recover up to 95% of the toluene solvent used, making it suitable, for example, for flexography printing (Silferberg *et al*., 1998). Once separated, the toluene and water can be reused. For gravure, thermal or catalytic afterburners are needed because of the numerous solvents used.

For very high VOC concentrations, condensation can be used. Normally condensation is performed as a pretreatment for other methods. The cheapest and simplest method is the direct contact condenser. It is sprayed into the solvent-laden gas flow. The cryogenic method is used where high solvent recovery (up to 99%) is required (Giddings *et al*., 1991).

Incineration costs are very high, especially for small plants. In a large wood-coating company processing 10,000 m^3 of wood annually, annual capital costs of around 225,000 ECU and operating costs of around 13,000 ECU have been estimated assuming a 10-year lifetime and a 5% interest rate. In a middle-sized company treating 1,000 m^3 of wood annually, capital costs would be 135,000 ECU and operating costs would be 20,000 ECU. Compared with the turnover, the costs are too high for the incineration technique to be an attractive alternative. The number of coating sites in the EU before Sweden, Austria, and Finland became members was 9,000. The average site processes slightly more than 1,000 m^3 of wood annually, and thus corresponds to a middle-sized site, assuming that around 30 l of solvent per cubic meter of coated wood is used. Thus incineration can be considered best practice at only a few plants (Giddings *et al*., 1991).

In one example of heatset offset printing, the annual capital and operating costs of a regenerative thermal system were only 60,000 ECU (assuming a 5% interest rate). The cost of a catalytic cleaning system was approximately 15,000 ECU/year higher. The cost of a recuperative system was estimated to be around 150,000 ECU per year – much higher than the cost of a regenerative thermal system or catalytic afterburner. The printing plant size in this example was not reported (Silferberg *et al*., 1998). Vapor flows and concentrations to be treated are different in the printing and wood furniture industries. In the latter case, it has been claimed that the incremental costs of a catalytic afterburner would be 20% lower than those of thermal burning (Johansson *et al*., 1984).

If exhaust flow is high but VOC concentration is low, biofilter technology and adsorption with activated coal are economically more attractive than incineration and can be considered best practice in large mills (Johansson *et al*., 1984). In the case of wood preservation, the costs of adsorption with activated carbon have been estimated to be half the costs of incineration facilities. Costs are also lower with flexography and gravure printing (Klimont *et al*., 1997).

10. Summary: Comparison of environmental practices in the forest cluster industries

Figures 10.1 to *10.6* illustrate the differences between forest cluster branches in the “cost, quality, environment” framework when improved environmental performance is the goal. Arrows show the potential development with respect to environment, quality, and cost. Three types of emissions to the air and emissions to water are illustrated.

Quality loss or additional costs are usually the alternatives when improving environmental performance. The illustrations below assume that companies mainly choose additional costs over quality loss.

The forest cluster is not a major polluter with respect to NO_X and SO_2. The environmental performances of the branches are good or average (*Figures 10.1* and *10.2*).

Currently available technologies to reduce NO_X emissions are not as effective as those used to reduce SO_2 emissions. The costs for introducing those technologies are relatively high.

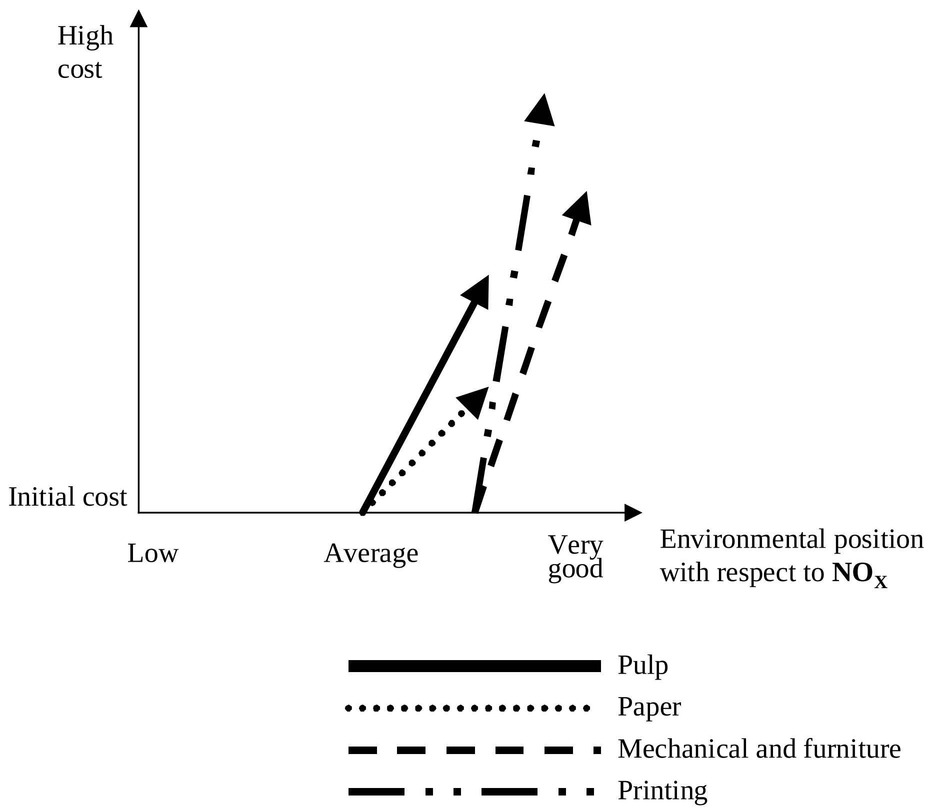

Figure 10.1. Cost, quality, and environmental framework for NO_X.

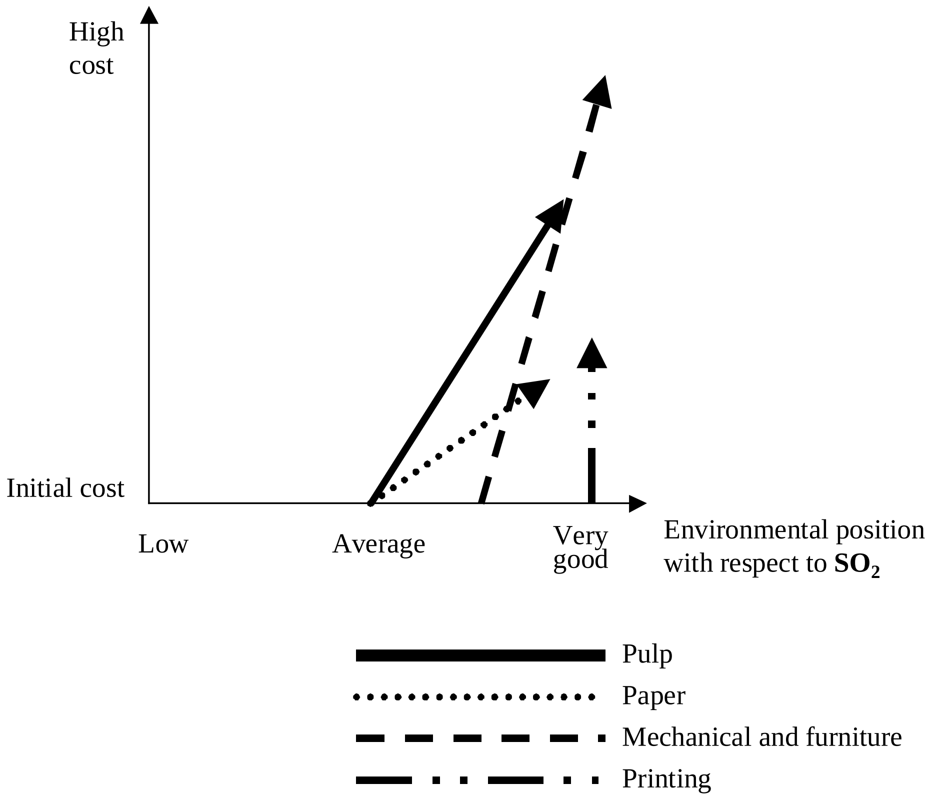

Figure 10.2. Cost,quality, and environmental framework for SO_2.

The cost efficiency of decreasing emissions from the energy boilers of the paper industry is not greater than that for the pulp industry. But contrary to the pulp industry, the paper and paperboard industry can extend the environmental effect, to the whole value chain by using lean material solutions.

NO_x emissions from the printing industry originate mainly from thermal incineration. Opportunities to reduce those emissions have so far not been investigated.

With respect to NO_x and SO_2 emission reductions, the mechanical forest industry and wood furniture building industry are in a worse position than the pulp and paper industry. That industry benefits from economies of scale when installing end-of-pipe technologies. NO_x and SO_2 emissions from the mechanical forest industry and the wood furniture building industry are, however, low.

VOC emissions from the forest cluster are a significantly greater problem than NO_x and SO_2 emissions (*Figures 10.3* to *10.5*). The printing industry, wood furniture coating, and wood preservation cause the most emissions.

VOCs from paper and paperboard manufacturing mainly result from the use of VOC-containing chemicals. These chemicals can often be replaced, but only by jeopardizing the quality. The pulp industry could reduce its VOC emissions by collecting non-condensable gases more efficiently. The equipment enabling such collection may be very costly in the existing mills.

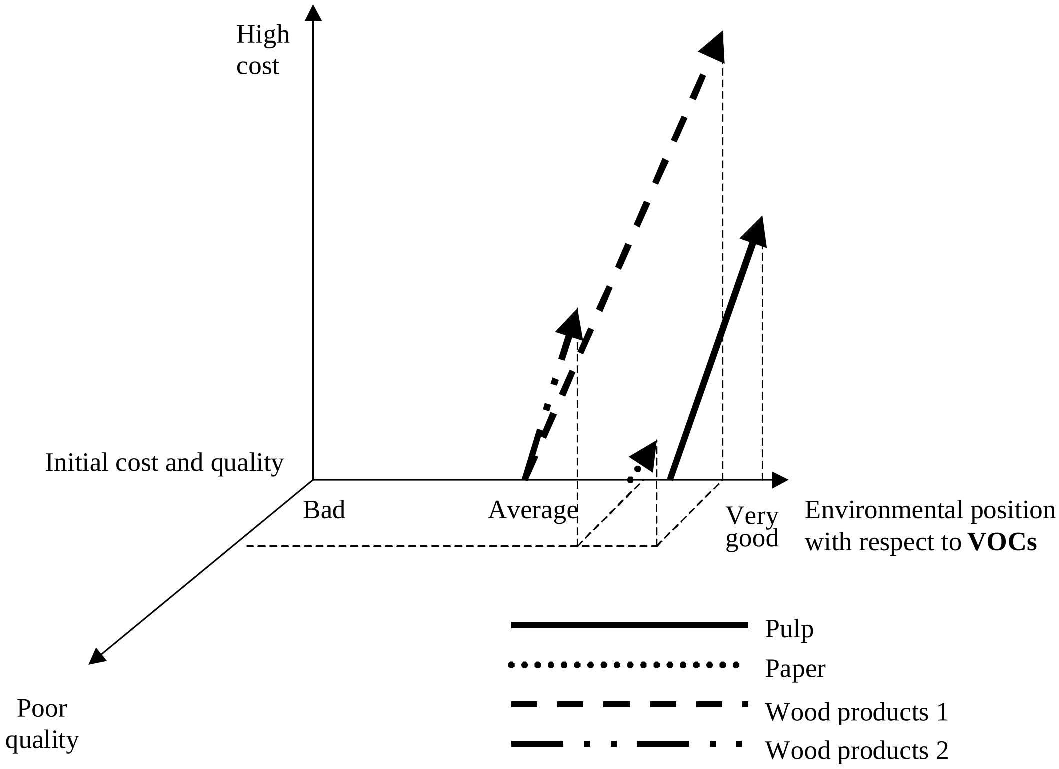

Figure 10.3. Cost, quality, and environmetnal framework for VOCs.

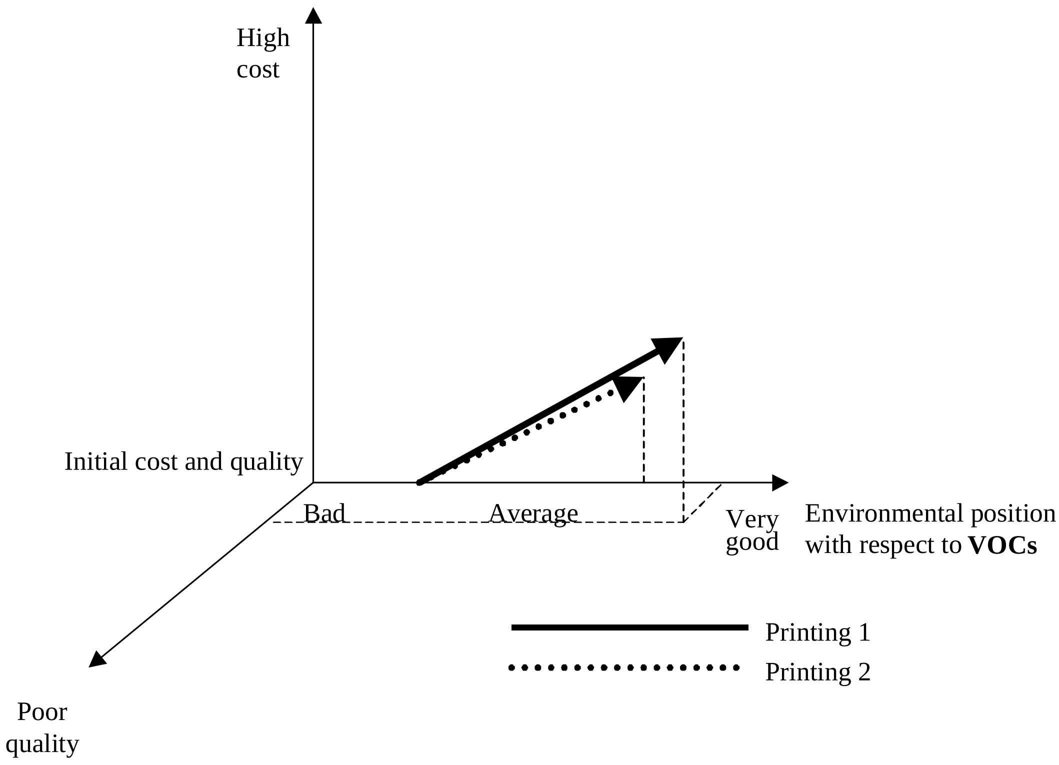

Figure 10.4. Cost, quality, and environmental framework for VOCs.

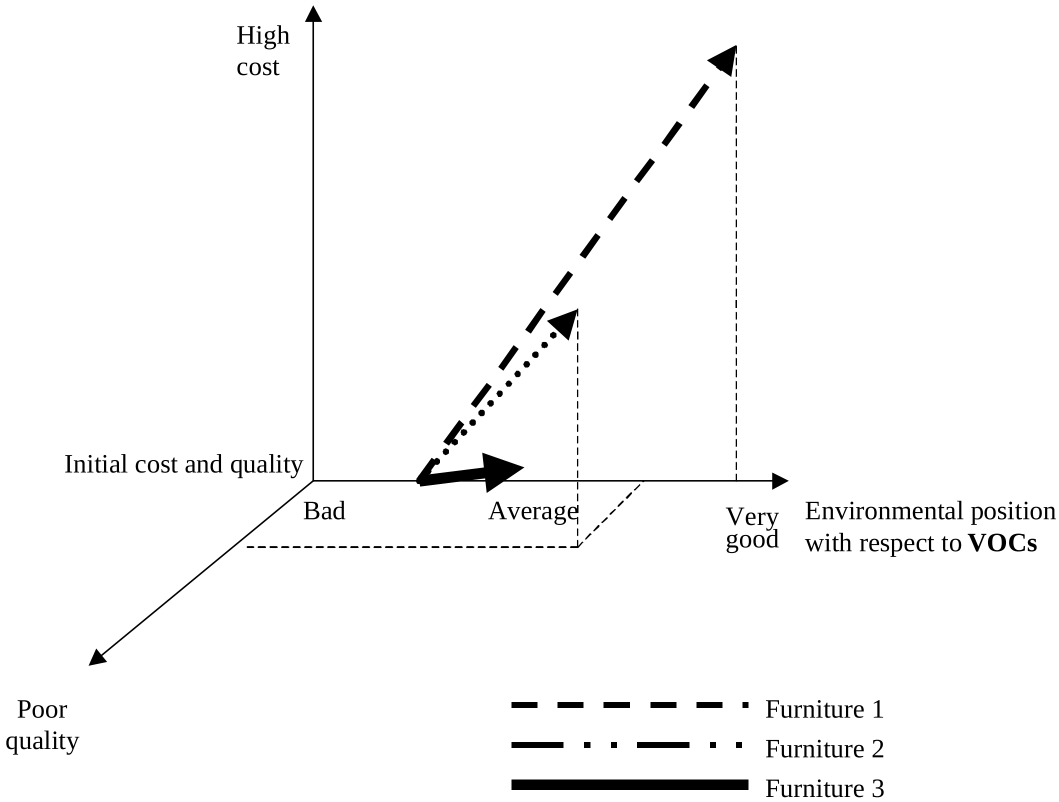

Figure 10.5. Cost, quality, and environmental framework for VOCs.

Wood preservation has two main strategies available to it. Thermal incineration and adsorption are effective methods, but they lead to extremely high costs relative to the small size of the companies in operation. Another alternative is to replace part of the solvent-based preservative within water- or creosote-based preservatives. This measure does not improve the environmental performance as much as the first alternative. When requirements are demanding, quality problems may occur. Costs are lower, arising mainly from retrofitting a plant to work with water.

There are two main alternatives available to the printing industry. First, in flexography and gravure printing, significant environmental improvements are possible. Switching from solvent-based inks to inks containing few VOCs has economic benefits resulting from the lower disposal costs. In many plants, however, the use of inks other than solvent-based inks requires costly layout changes because of the higher drying capacity required. If gravure is used for packages solvent-based inks are required and costly incineration equipment is needed. Gravure with water-based inks also causes problems with uncoated paper and deinking. In offset printing, the solvent content in the dampening solution can be reduced, resulting in economic benefits. Some problems may occur with the quality. To sum up, the first alternative improves the environmental performance considerably. The costs are relatively low and the quality problems are minor.

Another alternative is to concentrate on reducing emissions only where low costs are required and quality problems do not occur. The improvement in the environmental performance can still be high.

For wood furniture production there are at least three main alternatives. First, incineration and adsorption are very effective if solvent-based coatings are used. The costs involved are, however, unacceptably high for most plants.

Second, switching to other coatings is possible. However, where high quality is required, problems may occur. The costs of retrofitting an existing plant — for example, for the use of water-based coatings — have to be taken account. Environmental performance can be improved considerably.

Third, introducing new coating application methods and recovering the used solvent results in reasonable improvement in environmental performance. Disposal cost savings may result in economic benefits. Quality should not to be jeopardized. This measure can be carried out only in some coating plants.

Emissions to water are a major problem in the pulp industry (*Figure 10.6*). Techniques for great improvements exist, but the costs involved are great. The paper industry is in a slightly different situation. Its characteristic emissions to water are lower, and introducing a new external treatment plant would be an investment with a very low environmental efficiency. However, through lean resource technologies – for example, by closing the water circulation – environmental performance can be improved more efficiently.

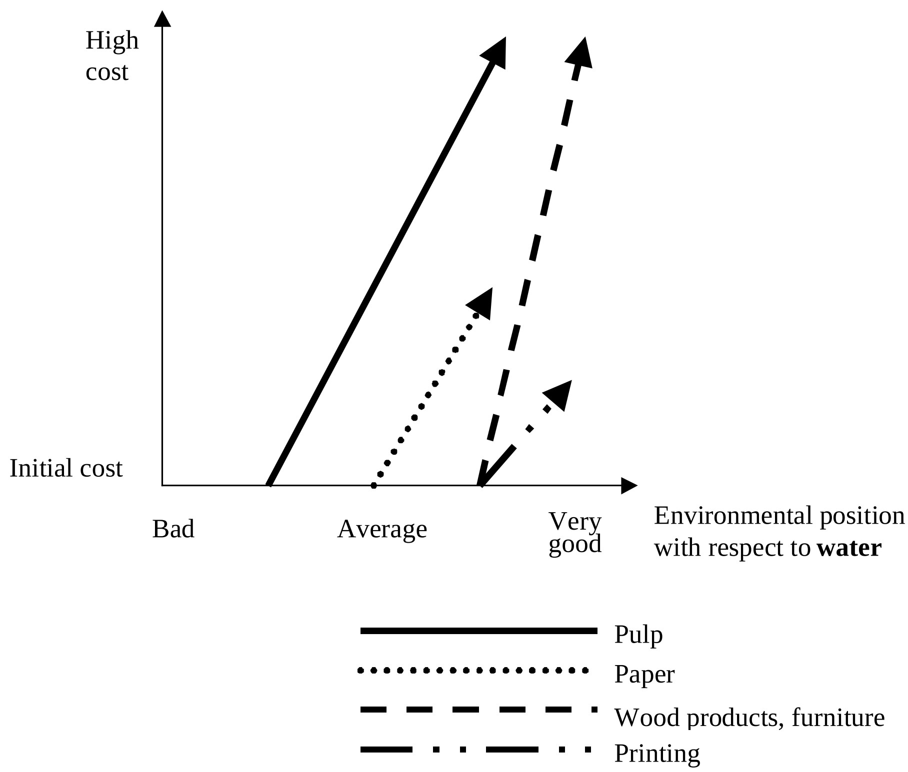

Figure 10.6. Cost, quality, and environmental framework for water.

Emissions to water from other forest cluster branches differ from those from the pulp and paper industry, containing fewer organic compounds and more toxic substances. Data on the amounts and effects on environment are not readily available.

The printing industry can reduce silver-containing effluent discharges by recycling water. The investments required are minor and the savings in the disposal costs can be substantial.

As a whole, the mechanical forest industry discharges only small amounts of effluents. However, the wet process used in fiberboard manufacturing is a major source of organic compounds relative to the industry's size. Because of the small average plant size, installing the most efficient external treatment is not economically attractive.

Solid waste and energy are also discussed in this study, but presenting figures corresponding to those above is difficult. Best practices in solid waste control are often related to management practices. A high-capacity utilization rate in papermaking and the proper sorting of material in the mechanical forest industry are examples.

Improvements in net energy consumption are discussed in this study. Solutions are industry specific and general conclusions are difficult to draw (Kettunen, 1999a, 1999b).

11. Conclusions and recommendations

With respect to the environment, the forest cluster can be divided into two different groups. The chemical wood processing group is facing problems that deal more or less with organic compounds and water. The other branches are facing problems concerning VOC emissions and hazardous wastes.

In terms of environmental efficiency, the greatest development potential can be found in the printing industry concerning its VOC emissions. The paper and paperboard industry also has high potential for development, but the measures are not as straightforward as in the printing industry. The potential lies in innovations and in a willingness to reformulate the chain from pulp mill to paper mill and from paper mill to the customer.

Environmental best practices often differ between existing plants and those being planned. External abatement or end-of-pipe technologies are more attractive in the case of existing plants. Environmental best practice can also depend on the strategy for the future.

In the future, the forest cluster and especially the pulp and paper industry should be examined from a totally new perspective with respect to environmental efficiency. This study briefly discusses one of those factors, recycling versus dematerialization.

If a certain customer need can be satisfied by two products using different manufacturing processes, the more economical of the two should be used as long as required emission levels can be achieved using the process. Generally speaking, using virgin fiber is always better than using recycled fiber in terms of quality. If the manufacturing process, transportation, energy production, and final disposal are taken into account and environmental performance improves as a result of increasing the use of virgin fiber compared with recycled fiber, the latter should not be preferred, as is usually the case now. Because transportation still has greater importance with respect to emissions, waste paper is less environmentally efficient than virgin fiber in this respect.

So far, it has been obvious that recycled-fiber-based products are preferable from the environmental point of view. The result is that products made from recycled fiber have an embedded environmental value in their price. Waste incineration is not considered recycling. However, in the future more efficient waste incineration technologies and development of combustible fillers for paper, resulting in a biofuel-type of incineration, combined with cleaner pulping technologies may lead to a lower embedded value in recycled-fiber-based paper and higher attractiveness of incineration. Accepting virgin fiber as an environmental solution makes room for development of dematerialization which is closely connected with the use of virgin fiber only.

The forest sector has been examined from systems analytical perspective, for example, in IIASA’s Global Forest Sector model. Among the products included in the model are forest industry goods. It is possible to expand the equilibrium approach used by treating energy as a product. Its production facility, the waste incineration plant maximizes its profit just as forest industry goods producers do.

Models for analyzing the environmental impact of manufacturing processes and transportation, such as the RAINS model of IIASA, have been developed. Combining new types of equilibrium and emission models would make it possible to determine both the best structure for the forest industry from the environmental point of view as well as the kind of policy that is required to achieve it.

Appendix: Description of environmental practices in chemical pulping

Debarking

Drum debarking is the method usually used (Ministry of the Environment, 1997). Dry debarking has gradually taken over wet debarking. In the former, the consumption of water, and hence the emissions of organic substances, are much lower. It is possible to eliminate emissions. In dry debarking, the bark that is used for energy production has a lower water content, enabling better energy balance (Nordic Council of Ministers, 1993). Effluent from debarking is treated biologically. Use of biotechnically produced enzymes in debarking is under research (KTM, 1994).

Cooking

In a normal cooking process all of the alkali is added at the same time, leading to high alkalinity and hence to dramatic yield losses. In extended cooking, the alkali is added gradually by displacing black liquor and chemicals. The peak alkalinity is lower and thus yield loss is also lower. Consequently, the cooking process can be extended, resulting in a lower kappa value (i.e., a lower lignin content; Miller Freeman, 1991).

A typical extended cooking process, modified continuous cooking (MCC), is installed for a continuous digester by splitting the addition of white liquor and cooking in a counter-current mode toward the end of the cook. White liquor is normally added at three points: in the digester feed, between the impregnation vessel and the digester vessel, and in the counter-current cooking circulation line of the digester vessel (Miller Freeman, 1991). For existing mills, extended cooking can be installed only by splitting the addition of the white liquor and the cooking in the wash zone (Miller Freeman, 1991). The addition of a new pump and some piping are all that is required. The cost of the simplest extended cooking modifications can be very low; the corresponding kappa reductions are not available.

Extended cooking for the continuous process consists of the following alternatives: MCC, extended MCC (EMCC), and isothermal cooking (ITC). The EMCC process is the same as the MCC process, except that the white liquor is also added to the washing zone. ITC resembles the EMCC process. In the ITC process, the cooking temperature is kept constant at a somewhat lower level than the temperature in the EMCC process.

For batch cooking there are three alternatives: rapid displacement heating (RDH), Superbatch, and Enerbatch. In the first two cases, wood chips are penetrated with black liquor. In the Enerbatch process, in contrast, treatment with black liquor occurs after cooking with white liquor (Swedish Environmental Protection Agency, 1997). The problem with extended cooking is the increasing load in the recovery boiler. Some argue that when using extended cooking, oxygen delignification and bleachability are enhanced (Miller Freeman, 1991). When using extended cooking, fuel consumption in the lime kiln and steam consumption due to higher evaporation needs. If the recovery system is a bottleneck, introducing extended cooking may lead to significant capacity reduction. The ITC process has no adverse effects on capacity.

Washing and screening

Modern pulp-washing facilities normally recover at least 99% of the chemicals applied in the digester (Ministry of the Environment, 1997). The equipment is different for continuous and batch digesters. Diffusion time and temperature are the most important variables. Pressing is very effective in removing dissolved organic substances. Using CO_2 improves the washing effect (Ministry of the Environment, 1997). Other efficient washing methods are pressurized drum washing, atmospheric diffusion washing, pressure diffusion washing, and use of table washers (Miller Freeman, 1991). Vacuum washers have been gradually replaced (US EPA, 1993). Brown stock washing is an important stage in the prevention of dioxin formation in the first bleaching stage because it provids precursor compounds (Miller Freeman, 1991).

At modern mills, the screening process is closed (Nordic Council of Ministers, 1993). Improving cleaning and screening methods permits the use of simpler process and the utilization of low-quality fiber (KTM, 1994). These reduce emissions and improve yields. Closing the washing and screening stages is essential for reducing water consumption (Swedish Environmental Protection Agency, 1997).

Oxygen delignification

Oxygen delignification has been introduced as one method to reduce chlorine usage in bleaching. Oxygen delignification takes place in the same water circulation as in other unbleached pulp processes. This is the reason why oxygen delignification is not counted as a bleaching plant. In oxygen delignification, oxygen with oxidized alkali is used to remove lignin before bleaching. Organic material dissolved within oxygen delignification can be recovered and sent to the chemical recovery system (Ministry of the Environment, 1997).

If the oxygen tower and additional washing stages are located between the brown stock washer and the bleach plant, implementing oxygen delignification in an existing plant is easy (Miller Freeman, 1991). In other situations, implementing oxygen delignification may not be attractive because of the required layout changes.

Evaporation and recovery boiler

The cleaned condensates should be reused after treatment in an end-of-pipe equipment. Possible uses are in bleached or unbleached pulp washing (JRC, 1998).

By adding a superconcentrator in the evaporation stage, a dry solids content of 80% can be achieved. Higher temperatures resulting from the higher dry solids content and modified incineration conditions lead to lower sulfur emissions (Swedish Environmental Protection Agency, 1997). Almost complete elimination of TRS emissions is possible. When combusting black liquor at higher temperatures, more sodium is released, which further binds released sulfur, reducing sulfur emissions considerably. In contrast, dust emissions will increase. Also, NO_x emissions have a tendency to be higher when the combustion temperature is increased.

Pressurizing the liquor within evaporation permits a higher temperature and consequently viscosity can be lower. Low viscosity is prerequisite for pumping the black liquor for combustion. A dry solids content of 80% can be reached. Another method for achieving lower viscosity is heat treatment. Because of the reduced sulfur emissions, the layer protecting the recovery boiler material contains more sulfur and its melting temperature is lower, leading to corrosion problems.

A higher dry solids content increases the capacity of the recovery boiler (Ministry of the Environment, 1997). When extended cooking or oxygen delignification is used, increasing the dry solids content is often required to maintain the same production level.

NO_x emissions can be reduced by at least 30% by reducing the amount of air led to the boiler's combustion zone and by about 50% through noncatalytic reduction with the addition of urea to the recovery boiler (Nordic Council of Ministers, 1993). NO_x is then reduced to nitrogen gas (SNCR process).

Lime kiln

In the causticizing process, green liquor is converted to white liquor. Lime mud ($CaCO_3$) removed from the green liquor is used in regenerating new lime (CaO), which is then used to generate white liquor. New lime is produced by burning lime mud in a lime kiln. External fuel is usually needed, which usually causes SO_2 emissions (Ministry of the Environment, 1997). The level of SO_2 emissions is even higher if malodorous gases are burned in the kiln. (Nordic Council of Ministers, 1993)

By burning malodorous gases in the lime kiln, the emission of TRS can be cut almost completely. This measure requires relatively low capital investments and there is no need for an extra furnace. Malodorous gases can offset approximately 15% of the external fuel requirements (Swedish Environmental Protection Agency, 1997). Formation of SO_2 is partially eliminated as a result of its absorption by sodium carbonate in the lime mud. However, the absorption capacity of sodium carbonate has a limit. The more malodorous gases that are burned in the lime kiln, the higher the sulfur emissions. The emission of sulfur can be reduced by scrubbing the strong gases before incineration.

By using improved lime mud washing, in which white liquor is washed away from the lime mud, the sulfur emissions can be decreased and dryness can be increased, leading to a reduction in the need for extra fuel (JRC, 1998; Costs app 1:6). Lime losses can be further reduced through better green liquor clarification and improved lime kiln instrumentation and controls (Miller Freeman, 1991). The level of NO_x emissions from the lime kiln depends on the way air is fed to the kiln and the burning temperature.

Spill control

Spills cause considerable emissions to water. Unlike in the techniques presented above, the problem of spills can be solved to a great extent by developing monitoring and management practices and installing good gaskets. A detection apparatus for identification of spills is a prerequisite for avoiding spills.

One of the problems with spills during external treatment is that the chemical balance is disturbed and hence the efficiency of the treatment is lower (US EPA, 1993).

Spill problems become greater when production is running at full capacity. Disturbances in some part of the process may lead to overflows in other stages. Therefore, buffer volumes or separate tanks in each process stage are recommended (JRC, 1998).

If spills occur, a spill collection system can prevent their entering wastewater treatment directly. A so-called weak spill can be led to a spill lagoon and then to effluent treatment if facility loadings allow. A concentrated spill should be led to a spill tank and then to a black-liquor storage facility. Installing a spill collection system at an existing mill can be costly (US EPA, 1993).

Bleaching

The bleaching stage is perhaps the most problematic element of a bleached pulp mill with respect to the environment. The bleaching plant is often the only part of the mill with a permanent effluent flow. Large amounts of chemicals are produced and used.

The current trend toward closed water circuits increasingly concerns the bleaching stage. After introducing TCF-bleaching, the amounts of effluents have been reduced to levels as low as 10 m^3/ton (expert opinion). This is a huge difference compared with the standard pulp mill discharge of 100 m^3/ton of effluents. The main reason why TCF bleaching has enabled such low emissions to water is that the corrosive effect of chlorine is not present.

Emissions from bleaching can be decreased by reducing the kappa number of the entering unbleached pulp to the lowest acceptable level. In doing so, the amount of chemical needed in the bleaching stage is reduced. Uniform pulp quality also plays an important role (Ministry of the Environment, 1997).

The reduction of effluent from the bleach plant means that water and chemicals must be partially reused (Renberg and Axegard, 1998). This is true for TCF pulp mills, but when chlorine chemicals are used, the reduction potential is much lower because of the corrosion problem with chlorine compounds.

When discussing recycling options, alkaline bleaching filtrate is a smaller problem from an environmental point of view because of the alkalinity of the cooking chemicals. Acid filtrate, in contrast, cannot be transferred to an unbleached pulp mill (Swedish Environmental Protection Agency, 1997). On the other hand, alkali filtrates contain much more CODs than do acidic and neutral filtrates, which is why it is crucial that they be recycled (Renberg and Axegard, 1998). Not all the filtrates can be integrated into the recovery system because of the capacity limitations (JRC, 1998). However, a part of the alkaline filtrate can be returned to the unbleached pulp washing stage or causticizing stage. This reduces the requirement of separate evaporation capacity. Acidic filtrates are circulated in the bleaching plant and excess filtrates are led to separate equipment for treatment, including evaporation, condensate treatment, oxidation, and salt treatment. Excess filtrates are replaced by cleaner water due to the enrichment of the chemicals in the bleach plant circulation water. The vaporized water should be reused. After such treatment, the only effluents from the bleaching plant are part of the condensates and salt dilution (Myréen, 1997). To keep the clean water concentration as high as possible, extra storage for water is necessary. If both alkaline and acidic filtrates are reused as described above, two counter-currents are needed, one alkaline and one acidic (JRC, 1998). At mills using chlorine-containing chemicals, separate treatment of the acidic effluent from the bleach plant by evaporation and incineration is possible (Nordic Council of Ministers, 1993).

Among bleaching chemicals, chlorine has the best selectivity, which is important for yield. Chlorine compounds are not very soluble in water. If chlorine is used, the pulp and paper will still have a certain concentration of chlorine (Miller Freeman, 1991).

When using peroxide as a bleaching agent, chelators such as EDTA are needed to prevent the degradation of the peroxide. The chelators currently used are not very biodegradable (KTM, 1994). Chelators contain nitrogen, and thus nitrogen emissions are higher.

Comparing the environmental externality of ECF and TCF bleaching is difficult. On the one hand, when using TCF, AOX emissions are practically zero. On the other, TCF requires more electricity, the yield is reduced, and more chemicals are used (Ministry of the Environment, 1997). Organic material from TCF bleaching biodegrades more easily than material from ECF bleaching.

Enzyme treatment has been introduced as a cost-efficient pretreatment of pulp before bleaching. Hemicellulose-degrading enzymes are normally used. Xylanases have been found to be the most effective. By using enzymes, the use of chlorine chemicals can be reduced further. The enzyme treatment should occur prior to a conventional bleaching (Swedish Environmental Protection Agency, 1997). Brown-stock storage can function as a reaction vessel. Enzymes are added after brown-stock washing (US EPA, 1993). A small yield reduction can be observed when enzymes are used.

End-of-pipe technologies and auxiliary boilers

Emissions to the air

The emission of gaseous compounds, especially SO_2, from a certain source can be reduced by at least 90% by installing a scrubber. This method is no longer so crucial because of the cost-efficient method of using a higher dry solids content when combusting black liquor (Ministry of the Environment, 1997; Saarinen *et al*., 1998). However, when evaporation capacity is limited, installing a scrubber can be the best solution. Scrubbers have a multi-stage absorbtion system consisting of three zones. The chloride zone cuts the emissions of chlorine; the washing zone cuts SO_2, TRS, and dust emissions; and the heat recovery zone recovers the energy (Confederation of European Paper Industries, 1997).

Sulfur is mainly returned to the process. Increasing sulfur content results in corrosion and problems in the pulp quality (Ministry of the Environment, 1997; expert opinion).

Cyclones and electrostatic precipitators are effective in reducing the emission of particles and dust in the flue gas from the lime sludge and the bark boiler (Saarinen *et al*., 1998). The reduction efficiency of cyclones for dust is around 80% and that of electrostatic precipitators is 90–99.5%

The most highly polluted condensates that come from evaporation must be treated in a stripper. As much of the total condesnsate volume as possible should be used in the causticizing and pulp washing steps (Nordic Council of Ministers, 1993; Ministry of the Environment, 1997; Miller Freeman, 1991).

For auxiliary boilers, such as bark boilers, using low-oxygen-burning technology reduces NO_x emissions, changing to cleaner fuels is the most effective way to reduce NO_x emissions. Emission-reduction efforts have been mainly targeted at sulfur emissions, while NO_x emissions have even increased with production (Pinkerton, 1998).

Emissions to water and solid waste

Solid waste is defined as material that is removed from use and disposed of. Solid waste consists of mechanical, biological, and chemical sludge from wastewater treatment plants; dust and slag from boilers; dregs from green and white liquor in the chemical recovery system; lime mud and bark from wood handling; and organic and inorganic waste from the whole operation.

Solid waste is mainly produced by primary and secondary treatment of effluent (Miller Freeman, 1991). Consequently, both solid waste treatment and external treatment of water are discussed in this report.

Bark boilers usually have enough capacity to burn the sludge generated by effluent treatment. A lime kiln or a separate boiler can also be used (Swedish Environmental Protection Agency, 1997).

A fluid bed system, which can be used in bark boilers, is a way to combust hard-to-burn fuels. The flue gas is cleaned by a dry scrubber or a fabric filter. A low combustion temperature or fluid bed system results in low NO_x emissions (Miller Freeman, 1991).

Ash from bark boilers can be used as fertilizer, depending on national regulations on fertilizers use (Confederation of European Paper Industries, 1997). This option is also possible for sludge. The problem with that is the enrichment of heavy metals. The problem still exists even if the process is closed. Separating the heavy metals from the ash by extracting is under research (KTM, 1994).

External treatment of effluents can be done mechanically (primary treatment), biologically (secondary treatment), or chemically (tertiary treatment), or by using a combination of these technologies. Practically speaking, with respect the emission level range presented in the BAT reference document, the use of both mechanical and biological treatment is required. External treatment aims at removing high-molecular substances (long-term influence) and low-molecular substances (toxic influence), and handling of sludge in a proper way (Swedish Environmental Protection Agency, 1997). The adoption and development of external treatment methods is probably the main reason for the considerable reduction in emissions to water since 1970.

A sedimentation, filtration, or flotation step is necessary at the first stage (Nordic Council of Ministers, 1993; Ministry of the Environment, 1997). Primary treatment removes the majority (even over 90%) of the solids.

Primary and chemical treatment have been combined at some non-integrated mills and at many Swedish kraft pulp mills (Ministry of the Environment, 1997). The mechanical treatment of effluents from debarking is usually done in a separate section. Adoption of dry debarking has considerably reduced the amount of effluents from debarking plants. Use of evaporation technology to treat effluents can be a step toward a closed system of wood handling (Finnish Forest Industry Federation, 1998).

Aerobic and anaerobic biological treatment are used. Aerobic treatment is much more common. Activated sludge treatment and aerated lagoons are the most typical methods. The difference between aerobic and anaerobic treatment is the use of oxygen in the aerobic process. The anaerobic process produces methane, which can be used for energy production; moreover, less sludge is produced and less energy is needed. The problem with the anaerobic process is its sensitivity to some compounds, which is why the process is not recommended for kraft pulp mills (Miller Freeman, 1991; JRC, 1998, Nordic Council of Ministers, 1993).

An aerated lagoon can be converted for extended aerated activated sludge treatment. In the activated method the sludge is recycled, increasing the amount of time the sludge spends in treatment and hence reducing the BOD emissions. Conversion has been carried out in some Swedish mills (Södra, 1998; AssiDomän, 1998).

Emissions to water depend on effluent volume. To work properly, bacteria at the treatment pool need a certain amount of BOD and nutrients (N and P), that is, a minimum discharge concentration of effluent. If the effluent concentration is high – in other words if freshwater consumption has been reduced – emissions to water are relatively low. Furthermore, the sedimentation step after biological treatment allows the penetration of a certain concentration of solids. If the amount of effluent is higher, and hence the concentration is lower, this penetration is relatively high. Only the COD discharge is independent of the amount of effluent (Lahti-Nuuttila, 1998).

The anaerobic method can be used as support treatment at CTMP mills as discussed in Section 3. Polluted condensates contain readily biodegradable compounds and can be treated effectively in an anaerobic unit, followed by an aerobic unit for the rest of the effluents.

Primary and secondary treatments generate a large amount of solid waste. Sludge from primary treatment accounts for 1–2% of production. If incinerated, auxiliary fuel is often necessary if much inorganic material is involved and the dryness of the sludge is low. The dry solids content should be over 40% to achieve positive net energy production. A dry solids content of approximately 40–50% can be reached with screw pressing (Saarinen *et al.*, 1998). The cost of the screw press is around 0.5 million ECU (Enso, 1997b). When mixing with wood, solid waste auxiliary fuel is not needed (Ministry of the Environment, 1997). The incineration efficiency can be increased further by pressing or drying the bark (Swedish Environmental Protection Agency, 1997). Landfilling instead of incineration can be better solution as far as air emissions are concerned. The higher the dry solids content, the more economical the incineration alternative.

Other disposal methods include returning the sludge to the fiber system or sending it to a landfill. If it is returned to the fiber system, careful screening is required (Miller Freeman, 1991).

In chemical precipitation, flocculation followed by a sedimentation, flotation, or filtration step are used. The last three options separate the sludge. Reduction of the emissions of suspended solids, colloids, and phosphates, and to some extent large organic molecules, can be accomplished (Nordic Council of Ministers, 1993; Confederation of European Paper Industries, 1997). Coagulant agents are used to destabilize dissolved substances. Chemical coagulation effectively reduces phosphorus (Ministry of the Environment, 1997). Chemical treatment must be done for coating kitchen effluents.

Chemical precipitation is used as a tertiary treatment only at Japanese kraft pulp mills. The effectiveness of combined mechanical, biological, and chemical precipitation is very high. A so-called polishing pond is a moderate tertiary treatment alternative with a low reduction of waste. This method is used in some mills in Europe,

When using combined mechanical treatment, activated sludge treatment, and chemical precipitation, the following reductions can be observed: 80–90% of phosphorus, 30–60% of nitrogen, 80–90% of COD, 80–90% of AOX, and over 90% of BOD (JRC, 1998). When using mechanical treatment and aerated lagoons the reductions are approximately the following: 50–90% of BOD, 30–60% of COD and AOX. Replacing the aerated lagoon with activated sludge treatment, the reductions are approximately the following: 80–95% of BOD, 50–80% of COD, and 40–70% of AOX (Confederation of European Paper Industries, 1997).

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