4. The non-linear relationship between paper recycling and primary pulp requirements\textsuperscript{95}

4.1. Introduction

Renewable resources can be used for energy or materials; wood can be combusted, but also used to produce paper. Materials efficiency is usually increased by increasing recycling. This Chapter studies the effect of waste paper recycling on the use of renewable energy and non-renewable energy. Table 4.1 shows the resources studied in this chapter in the context of the resource matrix.

Table 4.1: renewable energy vs. renewable materials

<table>
<thead>
<tr>
<th>Resource use</th>
<th>Non-renewable</th>
<th>Renewable (exhaustible)</th>
<th>Non-exhaustible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials (non-dissipative)</td>
<td></td>
<td>Pulpwood</td>
<td></td>
</tr>
<tr>
<td>Energy (dissipative)</td>
<td>Fossil fuels</td>
<td>Bio-energy</td>
<td></td>
</tr>
</tbody>
</table>

Note: simplified version of Table 1.1

An important option for reducing GHG emissions is the substitution of carbon-intensive fossil fuels such as coal or oil by less carbon-intensive, renewable energy sources such as solar, wind or biomass (OECD 2001b). Currently, biomass is the main renewable energy source with the potential to be implemented on a substantial scale because of its relatively low costs and its ability to substitute for coal within the existing electricity infrastructure (Berndes et al. 2003; Hall & Scrase 1998; Klass 1998).

Biomass is a resource that is also widely used for materials purposes, one of which is paper (and related products). About one third (35%) of the total wood production in the European Union is for pulp intended for papermaking (FAOSTAT 2001). The papermaking process can be briefly described as follows: After sawing, roundwood\textsuperscript{96} is slashed, debarked and chipped. The chips are then pulped,\textsuperscript{97} whereas the waste products (e.g. sawdust and bark) are used to produce electricity and heat (Genco 1998). The pulp is dried and pressed to form paper. Secondary pulp, produced from waste paper, can substitute for virgin or primary pulp.

\textsuperscript{95} Co-authors: Henri C. Moll and José Potting. Published in slightly different form in: Journal of Industrial Ecology, 2004, 8(3), 141-161.

\textsuperscript{96} Roundwood is defined as follows: “Wood in the rough. Wood in its natural state as felled, or otherwise harvested, with or without bark, round, split, roughly squared or other forms (e.g. roots, stumps, burls, etc.).” (FAO 2001).

\textsuperscript{97} Pulping includes various processes. According to Genco (1998), “The principal wood-pulping processes (…) are stone groundwood, (…) sulphite, and the sulphate or Kraft process (…)”. In the current article, the stone groundwood process is referred to as the mechanical process, and the sulphate or Kraft process is referred to as the chemical process (the sulphite process is not considered in this article).
The use of biomass for paper production is intimately connected to waste management choices because waste paper is suitable for recycling back into paper or for energy recovery. If waste paper is recycled, secondary pulp replaces virgin pulp in the paper production process. Therefore, primary resource management and waste management influence each other, making trade-offs and synergies rather complex.

The relative merits of recycling versus incineration with energy recovery (both as alternatives to landfilling) have been the main focus in previous literature about waste paper management. From this literature, the following conclusions can be drawn (Beer et al. 1998; Blum et al. 1998; Finnveden & Ekvall 1998; IIED 1996; Rajotte 2000; Ruth & Harrington 1997b):

- Recycling, compared to incineration, leads to a lower use of biomass (pulpwood); and,  
- Recycling, compared to incineration, leads to a lower total energy use because the production of secondary pulp from waste paper is less energy-consuming than the production of primary pulp from roundwood; however,  
- Recycling, compared to incineration, leads to a higher use of electricity from the public grid which is presently predominantly fossil fuelled; and therefore,  
- Recycling leads to higher CO₂ emissions when compared to incineration.

One aspect of waste paper recycling that is not taken into account in the above literature is the fact that fibre recycling is limited due to physical constraints. Repulping of waste paper damages the cellulose fibres and decreases the ability of fibres to adhere to each other (Ellis & Sedlachek 1993). Fibres can be shortened as a result of damage during re-pulping and overly short, weak fibres are disposed during the washing process (Borchardt 1998). Typically, a fibre can be reused 3-5 times (Virtanen & Nilsson 1993). Therefore a permanent input of virgin fibre to the system is required (IIED 1996). Because the recycling of a single fibre is physically constrained, one can expect that theoretically, the relationship between recycling rates and resource requirements should be represented by a curved line rather than a straight one (Virtanen & Nilsson 1993). Also, analysis of country-level data from CEPI (BUWAL 1996; CEPI 2000) suggests a non-linear rather than a linear relationship between virgin fibre consumption and the use of recovered paper (as demonstrated later in Figure 4.2).

In this article, we investigate whether the physical limits on waste paper recycling can be theoretically described with a mathematical model which can be calibrated against available data and will produce the expected non-linear relationship between recycling rates and primary pulp requirements. Next, we explore whether that non-linear relationship leads to an optimal recycling rate with regard to energy consumption; that is, given the physical limits on recycling waste paper, whether an

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98 Pulpwood is defined as follows: “Wood in the rough other than logs – for pulp, particle board or fibreboard.” (FAO 2001).
99 This is in line with the observation that a carbon tax leads to less waste paper recycling (Gielen et al. 2001).
100 "Resource requirements," as used in this article, refers to primary pulp requirements. This term does not refer to land, ecosystem services, or other resources that come into play in the forest product chain.
101 It is common in the natural sciences to refer to the relationship described in this article as “non-linear”, although alternatively “curvilinear” is also used to express this relationship.
optimum recycling rate can be found where the total energy requirement\textsuperscript{102} is at a minimum. The study focuses on the pulp and paper industries because almost all energy and resource use for the production of paper from its raw materials is concentrated in the process phase of the life cycle.\textsuperscript{103} We also investigate the robustness of this optimum and discuss its relevance in the context of future developments both within and without the pulp and paper industries. Our modelling approach contributes to the work of Virtanen and Nilsson (Virtanen & Nilsson 1993) by adding precision to their expert expectation with regard to the energy efficiency of waste paper recycling.

4.2. System and model approach

Our method aims to quantify fibre damage during recycling and investigate whether this leads to a non-linear relationship between recycling rates and virgin fibre requirements. Ultimately, we want to determine whether this non-linearity leads to an optimum wherein the total energy requirement is at a minimum for a certain recycling rate. This was done in three separate stages:

- First, a substance-flow model was built to explore the effects of fibre damage in waste paper recycling in the paper and pulp industries. This model was supplemented with a mathematically-derived equation in which the virgin fibre input depends on the recycling rate and a set of constants. The equation derived from the substance-flow model was then calibrated with country data on recycling rates and wood pulp consumption and the corresponding set of constants was determined.

- Second, in order to estimate the significance of fibre damage during recycling – in terms of the total energy requirement – the consumption of energy resources from the derived equation was used to evaluate whether there is an optimum process energy requirement. The process energy requirement, waste paper consumption, and pulpwood consumption are expressed in terms of primary energy requirements and are presented as a function of the recycling rate.

- Third, the robustness of the optimum recycling rate is investigated by using the upper and lower values of the variables as input variables in order to determine the sensitivity of the model to uncertainties in data.

In our research, we aim to draw generic conclusions about waste paper recycling in the pulp and paper industries. In order to do so, the “system” was simplified by focusing on energy requirements (in terms of primary energy) of paper manufacturing in the member countries of the Confederation of European Paper Industries (CEPI).

\textsuperscript{102} ‘Total energy requirement’ is defined for this article as process energy + feedstocks, both expressed in terms of energy.

\textsuperscript{103} Typical energy and resource uses in different stages of the life cycle are as follows: <1GJ/t for forestry practices and transportation to plant (excluded), 0.4 GJ/t for capital stock (excluded), ca. 20 GJ/t purchased energy and ca. 2.5 m$^3$/t pulpwood for mechanical pulping and papermaking (included), ca. 15 GJ/t purchased energy and ca. 4.5 m$^3$/t pulpwood for chemical pulping and papermaking (included), and ca. 19 GJ/t purchased energy and ca. 1.5 t/t wastepaper for recycled pulping and papermaking (included) (Berg 1995; BUWAL 1996; de Boer 1998; de Castro 1992; Dielen & Eppenga 2001; EC 2000; Fraanje & Lafleur 1994; Rajotte 2000; Wiselius 1994). Total transportation (including waste paper collection) depends strongly on local conditions and energy use in transportation may go up as well as down under changing recycling scenarios (excluded) (Finnveden & Ekvall 1998).
this article, a conceptual framework of fibre length will be used as an indicator for all properties affecting qualitative aspects of fibres. The simplifications made here and their (possible) effects on the results are assessed in the discussion section.

There are several ways to present recycling rates (Berglund et al. 2002). This article defines recycling rates as recovered paper utilization (RPU) rates, that is, the use of recovered paper in a sector as a percentage of the total paper production in that sector (FAO/CEPI 2000). RPU rates are the preferred indicator for recycling where forest protection and energy conservation are concerned (Berglund et al. 2002).

4.3. Non-linearity in resource requirements

With higher recycling rates, fibres are reused more often, and this increases the chance that they are damaged beyond usability. Higher recycling rates therefore create the need to replace more secondary fibres with virgin fibres. CEPI (CEPI 2000) gives data about virgin fibre consumption and the use of recovered paper as a percentage of the total paper for every CEPI country. The plot of these data in (seen later in Figure 4.2) suggests that the relationship between RPU and virgin fibre inputs is non-linear rather than linear. We therefore further investigated this relationship.

In order to determine the particular kind of non-linear relationship that exists between virgin fibre requirements and recycling rates, waste paper recycling in a closed system was studied with a substance flow model (Kleijn 1999). The basic thought behind this model is that a virgin fibre replaces every fibre that can no longer be recycled. An overview of the model is shown in Figure 4.1.

This diagram assumes a closed economy for the recycling of waste paper in the paper and pulp industries. Virgin fibres enter the system through flow “z” into stock “S1”. Next, when the fibre is not recycled, it leaves the system through flow “F1”. When the fibre is recycled, we assume the fibre to have a certain probability that it will be shortened during the re-pulping process, expressed in the damage rate “y”. When the fibre is damaged, it leaves “S1” and enters “S2” through “F3”. When the fibre is recycled and not damaged it stays in “S1” for use and eventually for further recycling.

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104 Alternative measurements of waste paper recycling are
- waste paper net recovery rate: the amount of waste paper collected for reuse as a percentage of the adjusted paper and paperboard consumption,
- adjusted waste paper net recovery rate: the amount of waste paper collected as a percentage of the adjusted paper and paperboard consumption from which the non-recoverable paper and paperboard is deducted, and
- waste paper in fiber use rate: the amount of recovered paper used for paper and paperboard as a percentage of the total fiber used for paper and paperboard. (FAO/CEPI 2000).
Figure 4.1: Closed-system fibre recycling (example with N=4)

Note: N=4 indicates that the fibres in this model are damaged (and then recycled) four times. The boxes represent stocks of fibres of varying fibre lengths (S₁ – S₄) and the arrows with bowtie shapes represent flows (F). F₁-F₄ represent non-recycled fibre flows exiting the system. F₅-F₈ represent damaged fibre flows. “z” represents the new fibre requirement for the system. Because the system is closed, z = F₁+ F₂+ F₃+ F₄+ F₈, and the value of “z” in dynamic equilibrium is the model output. The cloud-shaped figures at the end of arrows F₂-F₄ and F₈ represent the boundaries of the system that is modelled.

The model equations are given in Appendix A.

The stocks “S₁” to “S₄” represent fibre stocks of different qualities in the system. Note that paper can contain fibres of mixed qualities. A fibre in “S₄” that is recycled but damaged is assumed to be disposed in the washing stage of the recycling process. When the model is run with chosen values of recycling rate (x) and damage rate (y), the value of the virgin fibre requirement (z) evolves in such a way that a dynamic equilibrium is finally achieved. The model is re-run several times with different values of “x” but a constant value of “y”. It becomes visible from the calculated “x” and “z” that the relationship between the recycling rate (x) and the virgin fibre requirement (z) is non-linear rather than linear (in a theoretic, dynamic equilibrium situation). This non-linearity shows similarities with the empirical country data on recycling rates and (relative) virgin fibre consumption in Figure 4.2. The next obvious step is to determine the exact relationship between “x” and “z” from the equations in appendix A and then calibrate that relationship against the data points plotted in Figure 4.2.
\[ z(x) = \frac{S_{\text{tot}} \cdot (x-1)}{\left( \frac{xy}{1-x+y} \right)^N - 1} \]  \hspace{1cm} \text{Equation 4.1}

With:
- \( x \) = recycling rate
- \( z(x) \) = virgin fibre pulp requirement as a function of the recycling rate
- \( y \) = damage rate
- \( N \) = number of stocks
- \( S_{\text{tot}} \) = the amount of cellulose fibres in stock as a percentage of the amount of produced paper

Equation 4.1 presents the mathematical relationship between the virgin fibre requirement \( z \) and the recycling rate \( x \), with \( z \) as a function of \( x \). Appendix A describes how this relationship was derived. A non-linear trend line corresponding with Equation 4.1 is fitted against country data by the least squares method and at a given \( N \). The calculated damage rate \( y \) and fibre stock \( S_{\text{tot}} \) for different values of \( N \) are summarized in Table 4.2; the relationship between “\( x \)” and “\( z \)” corresponding to values of “\( y \)” and “\( S_{\text{tot}} \)” found for \( N=3 \) is shown in Figure 4.2.

<table>
<thead>
<tr>
<th>Number of stocks (N)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage rate ((y))</td>
<td>0.331</td>
<td>0.565</td>
<td>0.800</td>
<td>1.035</td>
</tr>
<tr>
<td>Total fibre stock ((S_{\text{tot}}))</td>
<td>0.905</td>
<td>0.910</td>
<td>0.913</td>
<td>0.915</td>
</tr>
<tr>
<td>Accuracy ((r^2))</td>
<td>0.883</td>
<td>0.885</td>
<td>0.885</td>
<td>0.886</td>
</tr>
<tr>
<td>Recycled fibre share at 100% recycling</td>
<td>85.4%</td>
<td>82.9%</td>
<td>81.4%</td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that the solution of a model with a chain length of five stocks (i.e., five stocks connected analogously to the stocks in Figure 4.1; \( N=5 \)) is obviously not valid, because the damage rate \((y)\) cannot exceed the value of one (otherwise flows of negative matter occur). The solution of a model with a chain-length of one is also not valid, because that would imply a linear relationship between recycling rates and virgin fibre requirements whereas it was determined earlier that the relationship is not linear, but non-linear. Therefore the only possible integer values of \( N \) are 2, 3 and 4.

In the next section the values corresponding to a model with \( N=3 \) are used to illustrate how non-linearity affects tradeoffs between waste paper recycling and incineration. In the section on sensitivity analysis we will discuss how the value of \( N \) (and corresponding \( y \)) affects the outcomes. Figure 4.2 shows the calculated relationship between virgin fibre requirements and the recycling rate described by equation 1 and the fits for \( N=3 \) from Table 4.2. The dotted line represents a fictive situation with no fibre damage during the recycling process. The dots are country data. From the figure it can be seen that for low recycling rates the relationship appears to be approximately linear. Only at higher recycling rates does the relationship start to deviate from the dotted line and become non-linear.
Figure 4.2: Relationship between the recycling rate and the virgin fibre requirement (N=3)

Source: Data taken from (CEPI 2000; FAO/CEPI 2000).

Note: N=3 indicates that the fibres in this model are damaged (and then recycled) three times. The dotted line represents a fictive situation with no fibre damage during the recycling process; the trend line is constructed using the least square values method and weighted by actual paper production statistics for member countries of the Confederation of European Paper Industries, i.e.

\[ \sum_{i=1}^{m} \left( y_i - y'_i \right)^2 \cdot P_i \] is minimized (where: \( y \) = data values; \( y' \) = values of the estimated points; \( P \) = paper production; \( i \) = country index; \( m \) = country pool). Accuracy \( r^2 = 0.885 \).

4.4. Effect of non-linear relationship on energy requirements

Now that a non-linear relationship between recycling rates and resource requirements has been established (Figure 4.2), the next logical step is to see if this relationship leads to an optimal recycling rate. That is, whether an optimum can be found where the total energy requirement is at a minimum for a certain recycling rate. This section explains how the relationship from Figure 4.2, based on Equation 4.1 with N=3 for the number of stocks (see Table 4.2), was used to express the total energy requirement as a function of recycling rate.

The total energy requirement for paper manufacturing is the sum of process energy requirements (expressed in primary energy) and the caloric value of the materials feedstock (Equation 4.2) (IFIAS 1974). Because this research aims to study the energetic effects of the recycling rate, it is necessary to distinguish between virgin fibre paper and recovered fibre paper as shown in equation 3.
Total Energy Requirement = \( PE_{tot} + FS_{tot} \) \hspace{1cm} \text{Equation 4.2}

Total Energy Requirement = \( PE_{VFP} + PE_{RP} + FS_{VFP} + FS_{RP} \) \hspace{1cm} \text{Equation 4.3}

Where:
Total energy requirement = sum of the process energy and the caloric value of the materials feedstock (expressed in terms of primary energy)
PE = process energy requirement (expressed in terms of primary energy);
FS = energy content of feedstock requirement (expressed in terms of primary energy)
VFP = subscript referring to virgin fibre paper
RP = subscript referring to recycled paper

Because recycling rates are defined as RPU rates in this article, the amount of waste paper used for recycling can be derived directly from recycling rates. Pulpwood and waste paper are energy sources (they can be burned) and their so-called lower heating values (LHV)\textsuperscript{105} determine their energy content (IEA 2001; IFIAS 1974). The pulpwood feedstock is given in Equation 4.4, and Equation 4.5 gives the wastepaper feedstock. Equation 4.4 also contains a conversion factor (RWE, roundwood equivalents) to express virgin fibre pulp (\( z \)) in pulpwood (Dielen & Eppenga 2001).

\[ FS_{VFP} = z(x) \cdot RWE \cdot LHV_{RW} \] \hspace{1cm} \text{Equation 4.4}

\[ FS_{RP} = x \cdot LHV_{RP} \] \hspace{1cm} \text{Equation 4.5}

Where:
\( z(x) \) = virgin fibre pulp requirement as a function of recycling rates as given in Equation 4.1 (with \( \lambda = 3; y = 0.565; S_{tot} = 0.910 \))
RWE = roundwood equivalents, i.e. the amount of roundwood (m\(^3\)) required to produce a tonne of pulp (m\(^3\)/t)
LHV = Lower Heating Value, i.e. the caloric (MJ/m\(^3\))
RW = subscript referring to roundwood

The conversion factors (RWE and LHV) as used in Equation 4.4 and Equation 4.5 are shown in Table 4.3. It should be noted that they all depend on the pulping process concerned (see footnote 97). The heating values of the pulpwood depend on which tree species are used (Klass 1998; Wiselius 1994). The heating values of waste paper differ because waste paper from mechanical pulp contains more lignin (Niessen 1978).

\textsuperscript{105} Lower heating value (LHV) is the heating value of a fuel when excluding the vaporization heat for the water vapour, whereas higher heating value (HHV) is the heating value of a fuel when the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.
Table 4.3: Feedstock conversion factors

<table>
<thead>
<tr>
<th></th>
<th>minimum</th>
<th>maximum</th>
<th>typical</th>
<th>Unit and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundwood equivalent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for chemical pulp (RWE_c)</td>
<td>4.0</td>
<td>6.6</td>
<td>4.5</td>
<td>m³/t; (EC 2000; Fraanje &amp; Lafleur 1994)</td>
</tr>
<tr>
<td>Roundwood equivalent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for mechanical pulp (RWE_m)</td>
<td>2.4</td>
<td>2.6</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>LHV wood for chemical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pulp</td>
<td>7</td>
<td>11</td>
<td>9</td>
<td>GJ/m³; (Klass 1998; Wiselius 1994)</td>
</tr>
<tr>
<td>LHV wood for mechanical</td>
<td>6</td>
<td>10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>pulp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHV wastepaper chemical</td>
<td>11.09</td>
<td>15.68</td>
<td>15.50</td>
<td>GJ/t; (Beer et al. 1998; Klass 1998; Niessen 1978; Tillman 1998)</td>
</tr>
<tr>
<td>LHV wastepaper mechanical</td>
<td>16.32</td>
<td>18.39</td>
<td>17.15</td>
<td></td>
</tr>
</tbody>
</table>

Note: LHV = lower heating value; m³/t = cubic meters per tonne; GJ/m³ = gigajoules per cubic meter; GJ/t = gigajoules per tonne.

Paper manufacturers produce energy from their own waste streams (notably bark and, in the case of the chemical process, also “black liquor”), but also purchase external process energy in the form of electricity and heat. Different quantities are needed for producing recycled paper and virgin fibre paper (see Table 4.4).

Heat and electricity are not primary energy sources, but have to be produced from primary energy sources, which involves losses. Efficiencies are calculated for heat and electricity for the studied situation in CEPI countries for 1999 and weighted by the total paper production of the underlying countries. The calculated efficiencies are 36% for electricity and 76% for heat for CEPI countries on average (IEA 2001). The numbers used in the calculations are summarized in Table 4.4.

Table 4.4: Energy requirements for several pulping and papermaking processes

<table>
<thead>
<tr>
<th></th>
<th>Heat (GJ/t)</th>
<th>Electricity (MWh/t)</th>
<th>Total primary (GJ/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>aver.</td>
</tr>
<tr>
<td>Integrated kraft pulp and</td>
<td>14.0</td>
<td>20.0</td>
<td>17.5</td>
</tr>
<tr>
<td>paper mills</td>
<td>- purchased energy (= total energy minus energy from own waste)</td>
<td>1.0′</td>
<td>6.0′</td>
</tr>
<tr>
<td>Integrated mechanical and</td>
<td>0.0</td>
<td>6.0</td>
<td>3.0</td>
</tr>
<tr>
<td>semi-mechanical pulp and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>paper mills</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated recycled fibre</td>
<td>4.0</td>
<td>6.5</td>
<td>5.3</td>
</tr>
<tr>
<td>mills</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Derived from (EC 2000; IEA 2001).

Note: GJ/t = gigajoules per tonne; MWh/t = megawatt-hours per tonne; aver = average; min = minimum; max = maximum; ′ = estimate

Because recycling is defined as RPU in this research, the share of the processes are not the same as the recycling rate, but rather, have to be derived from feedstock consumption. Equation 4.6 and Equation 4.7 show how process energy depends upon recycling rates.
\[ PE_{VFP} = \frac{z(x) \cdot TPE_{VFP}}{S_{tot}} \]  
\[ PE_{RP} = \frac{S_{tot} - z(x) \cdot TPE_{RP}}{S_{tot}} \]  
\[ TER(x) = \frac{z(x) \cdot TPE_{VFP}}{S_{tot}} + \frac{S_{tot}}{S_{tot}} \cdot \frac{z(x) \cdot TPE_{RP}}{S_{tot}} + z(x) \cdot RWE \cdot LHV_{RW} + x \cdot LHV_{RP} \]

Equation 4.6  
Equation 4.7  
Equation 4.8

Where:
TPE = typical process energy (from Table 4.4)
TER(x) = total energy requirement (process energy + feedstock), as a function of x

Combining Equation 4.1 to Equation 4.7 gives Equation 4.8, in which the total energy requirement only depends upon the recycling rate (x), variables and conversion factors. Now the variables and conversion factors from Table 4.2-Table 4.4 are used with Equation 4.8 and the total energy requirement was plotted against the recycling rate (x). The results are shown in Figure 4.3. The relationships are non-linear. With regard to paper produced from chemical pulp, an optimum was found at a recycling rate of 93%. Regarding paper produced from mechanical pulp, an optimum was found at a recycling rate of 81%.

Figure 4.3: Total energy requirement (process and feedstock) for paper production at different recycling rates, expressed in terms of primary energy (GJ/t)

Next, the composition of the total energy requirement values were determined (shown in Figure 4.4). The lower (and darker) areas represent external supply of energy, typically fossil fuel based, for both processes. The horizontally-striped areas represent
pulpwood consumption and the vertical-stripped areas represent waste paper consumption.

A: Chemically processed paper

B: Mechanically processed paper

Figure 4.4: Composition of the total energy requirement for paper production at different recycling rates
4.5. Sensitivity Analysis

The calculations in the previous sections were based upon average or typical values and sensitivity testing is needed in order to gain insight in the robustness of the results and the usability of our approach. The sensitivity of the results was analyzed by substituting the constants and the typical/mean values with a range of different values in Equation 4.8. The results of the sensitivity tests are shown in Section 4.9 (Appendix B), and are further discussed here.

In the previous section, the value of N for the number of stocks was set at 3. Therefore, we started this sensitivity analysis by comparing the results when different values of N were used (and the corresponding values of y and S). The total energy requirement was not affected for small values of x, and just marginally for high values of x. The optimal recycling rate, however, ranged from 87% to 100% for chemical and 76% to 93% for mechanical pulping. The exact optimal recycling rates are of relative unimportance because around the optimums the graphs flatten, implying that any change in the recycling rate around the optimum will result in a relatively low change in total energy requirement.

Next, upper and lower boundary values for process energy requirements (Table 4.4) and feedstock conversion factors (Table 4.3) were used as inputs for the model. The degree of uncertainty (or variation) among input variables appears to be the most important factor affecting the outcomes. Variables and conversion factors regarding virgin fibre paper affect the left hand side of Figure 4.5, while variables and conversion factors regarding recycled paper affect the right hand side of the figure.

Finally, sensitivity tests were performed with more efficient electricity production. Regarding the chemical process, more efficient electricity production leads to a higher optimal recycling rate. Regarding the mechanical process, more efficient electricity production leads to a lower optimal recycling rate. From Figure 4.4 it can be seen that, in the case of the chemical pulping process, total external supply of energy (represented by the lower two areas in Figure 4.4, i.e., process recycling + process virgin) increases with increased recycling rates, while in the case of the mechanical pulping process external supply of energy decreases with increased recycling rates, which explains the results in the sensitivity testing. Heat production is already very efficient and significant increases in efficiency are not to be expected. Therefore, sensitivity analysis was not performed on heat production efficiency.

The general pattern that can be inferred from the sensitivity analysis is that, at low recycling rates, increasing waste paper recycling is energy efficient, but becomes less efficient at higher recycling rates (see Figure 4.5). This general pattern was tested by calculating the total energy requirements at recycling rates 10% higher and lower than the optimum value of x and then comparing these total energy requirements with the optimum total energy requirements. This is also shown in Appendix B. It was found that, close to the optimum total energy requirement, increasing or decreasing the recycling rate does not affect the total energy requirement significantly (≤0.3%).
Figure 4.5: Sensitivity analysis

Note: Labels A, B1, B2, etc. refer to the sensitivity tests as shown in appendix B
4.6. Discussion

4.6.1. On methodology
Comparisons of waste paper recycling versus incineration as alternatives for landfills have often been based on energy consumption in an life-cycle assessment (LCA) context (see Section 4.1). The fact, however, that fibre recycling is limited and therefore – on theoretical grounds – tradeoffs are expected to be non-linear is often not explicitly taken into account. By explicitly modelling resource dynamics in the paper and pulp industries, the research in this article was able to demonstrate the existence of a non-linear relationship between virgin paper requirements and recycling rates. The non-linear relationship was first derived, and next was calibrated against empirical data on recycling rates and virgin fibre requirements. Next, the influence of this non-linearity on the total energy requirement for paper production was calculated. The advantage of our analysis is that it is able to mathematically confirm a relationship that has not been confirmed using previous methods. With this relationship being established, it will be easier to understand the effects of policies regarding waste paper.

Both recycling rates and pulpwood consumption data are known on a national level (CEPI 2000), and thus can be compared. An advantage of using data on a national level is that differences in, for example, paper grades, can be assumed to be somewhat averaged-out and therefore generic conclusions can be more easily proposed. Moreover, the difference in fibre content between different grades of paper is quite small. On the other hand, where process energy is concerned, more detailed information is an advantage because process energy requirements may vary for different grades of paper.

4.6.2. Model simplifications and assumptions
The pulp and paper industries were modelled in this research in order to be able to draw generic conclusions regarding the issue of waste paper recycling versus incineration. In this section the most important simplifications and assumptions in our modelling framework will be discussed.

This research focuses on graphic paper (newsprint and printing & writing paper). Two grades of graphic paper (chemical and mechanical) are assumed to be representative of graphic paper. In reality, there are not only different grades of graphic paper, but there are also grades of paper other than graphic paper. These different grades of paper are often the result of recycled waste paper which was collected in mixed form. The different stocks in Figure 4.1 hold fibres of different length and could be seen as representing different grades of paper. Improving fibre flows with so-called cascade management (Tromp 1995a) is only implicitly represented in our model, but there is a theoretical relationship between cascade management and the chain length in the model. The consequences of the simplifications mentioned above for the outcome are: 1) focusing on a single type of paper neglects the possibility to use fibres rejected for graphic paper (F8 in Figure 4.1) for other purposes like sanitary paper, and 2) the outflow rates (non-recycled paper) in Figure 4.1 (F1, F2, F3, F4) are in actuality not equal to each other because, in practice, recycling focuses on high quality fibres (S1) rather than on lower quality fibres (S4). The consequences of the simplifications mentioned above for the outcomes are difficult to assess, but are expected not to change the general pattern found in the sensitivity analysis section.
In our research, some differences between countries have been averaged. In reality, however, countries are different. An important aspect of differences between countries is that an optimal recycling rate in a country can differ from the optimum recycling rate as calculated in this research. Nonetheless, the general pattern found in the sensitivity analysis section should be valid.

This article focuses on papermaking in so-called integrated pulp and paper mills, because of comparison reasons. All industries in this research are assumed to have implemented best available techniques (BAT) as described within the European Union’s integrated pollution prevention and control (IPPC) framework (EC 2000) and as summarized in Table 4.3. BAT describes a range of techniques, because efficiencies of plants can differ due to several factors, including plant size, the country where the plant is situated, the type of species used, the grade of paper produced, and so on. However, we are interested in the effects of fibre damage on energy efficiency in a generalized way and for the whole graphic paper sector. Therefore we use the average energy efficiency of the techniques described in BAT. The upper and lower boundaries of BAT values were used in the sensitivity analysis (tests B and C) to explore the effect of plant efficiency on the results.

Energy conversion efficiencies for electricity and heat are averages of CEPI-countries (weighted by the total paper production of each country). In reality CEPI-countries differ significantly (IEA 2001) in the efficiency of their electricity production, and as demonstrated in the sensitivity analysis, these differences influence the outcomes. Because both recycling and virgin fibre pulping profit from increasing efficiencies, the optimum recycling rate is rather robust regarding this aspect. Nonetheless, the optimal recycling rate will differ from country to country.

4.6.3. System boundaries
The total energy requirement for paper production is expressed in terms of primary energy, because the amount of wood not used for paper production can, alternatively, be used to produce electricity and thereby replace an equivalent amount of electricity produced by fossil fuels (the primary energy source for conventional electricity from the public grid).

As shown in the introduction, the process phase dominates energy requirements in the life cycle of paper production. Therefore, we focused our analysis on the process phase and therewith avoided the issue of forest management, in which lower levels of wood consumption under a recycling scenario are considered a benefit (as in many LCAs on paper recycling) (IIED 1996, p186). We consider this to have little impact on our overall conclusions because it is common practice in CEPI countries to use only certified roundwood, which is considered the most sustainable method of forest management, and wood from certified forests is considered to be the most sustainable virgin fibre source (Edel 2003). Strictly speaking, however, avoided wood consumption should be treated as an auxiliary benefit. The horizontally-striped areas in Figure 4.4 provide an indication of the amount of wood consumption which takes place under different recycling rates.

This analysis focuses on energy. Therefore, many important environmental impacts related to paper manufacturing are neglected. When other environmental impacts such as emissions are taken into account, recycling is – in line with our results – often
favoured over the other processes (EC 2000). One notable exception is that of chlorinated emissions, where the mechanical process for pulp production is favoured over both pulp production through recycling and the chemical process for pulp production (EC 2000). External supply of energy is related to GHG emissions because electricity production is largely based on carbon-intensive fossil fuels. Therefore conclusions regarding GHG emissions can be drawn from this research.

The model focus is on the European region, or, more specifically, member countries of the Confederation of European Paper Industries (CEPI). This is justified by the following arguments:

- Europe is self-sufficient in pulp and paper for over 90% of its paper consumption, which makes the system approximately closed,
- the state of technology does not vary strongly from country to country,
- there is enough variation in recycling rates to analyze the effects of different recycling rates, and
- data provided by CEPI is rich and consistent.

Because our theoretic model (Figure 4.1) applies to recycling in a closed system, it is important that not only the total systems, but also the individual countries can be seen as being approximately closed. In reality, the CEPI-countries are not closed systems because of significant trade between waste paper between these countries (FAOSTAT 2001). This trade results (in theory) in the mixing of waste paper qualities which levels out differences in waste paper qualities between individual countries. Therefore, the relationship that we found between waste paper recycling and virgin fibre requirements is probably in reality less curved than we would expect the relationship to be without trade.

### 4.6.4. Changes outside our system

Our model focuses on changes within the paper production and waste management system. Changes outside of the observed system, however, may affect the system -- as demonstrated in the sensitivity analysis, where the effect of more efficient electricity production was tested.

Our approach is static, implying that variables and conversion factors are constant. In reality, however, technological developments will influence in one way or another how pulp and paper is produced and used (Ruth & Harrington 1997a). Future and new technologies – such as genetic modified organisms (GMO) (Pilate et al. 2002), flexible electronic displays (Chen et al. 2003; Granmar & Cho 2005), alternative oxidizers (Weinstock et al. 2001), the enzymatic pulp bleaching process (OECD 2001e), and the use of xylanase as a pulp brightener (OECD 2001e) – will influence the environmental performance in a way that is beyond the scope our model to represent.

When biomass becomes, in time, more important as an energy source (see introduction), interactions between electricity production and paper manufacturing will increase. Increasing the use of biomass in the electricity sector will cause environmentally preferable recycling rates to shift towards more recycling because of the greater use of forest products for energy purposes.
In this research we focus on “a tonne of paper produced”. When, however, the focus expands to “a material with certain properties,” materials can substitute for each other, thereby not only changing the outputs and efficiencies of the pulp and paper sector but also influencing other sectors. Other materials can substitute for paper, but paper may also substitute for other materials (Hekkert et al. 2001). When the focus expands even more, e.g. to “getting the news” (different media such as newspapers, television, and internet can provide this service), substitutions become even more complex (Reichart & Hischier 2002). Therefore, the actual potential for energy savings regarding paper production is higher than our results indicate.

4.6.5. Validation of the model: comparing results with others

Based on our results, it should be noted that 0.91 (air-dry) tonne of pulp are required to produce one tonne of paper. This seems to be rather consistent with other sources in the research literature because 15% of the raw materials input in CEPI countries are non-fibrous materials, and the water content of air-dry pulp is approximately 3-5% (CEPI 2000). The Swiss Agency for Environment, Forests and Landscape – BUWAL – concludes that 900 kg of pulp per tonne of product is needed (BUWAL 1996).

In our analysis, the share of reused fibres in paper at a recycling rate of 100% is 83%, meaning that about 17% is too damaged to be reused and needs to be replaced by virgin fibres; Virtanen and Nilson calculated 75% to 80% (Virtanen & Nilsson 1993). Because our results are more directly based on empirical data, we conclude that fibre recycling is more efficient than previously assumed. These results imply that in CEPI countries, fibre can be recycled at least 5 times on average.

In our research the total energy requirement is 49 GJ/t for chemical paper and 47 GJ/t for mechanical paper. We compared these values with previous research. Tromp finds a total energy requirement of 40.2 GJ/t for graphic paper (Tromp 1995b); Castro finds a value of 49.8 GJ/t, though with relatively high figures for transportation (de Castro 1992); BUWAL finds a value of 40 GJ/t for recycled paper, 42 GJ/t for chemically-processed paper and 40 GJ/t for mechanically-processed paper (BUWAL 1996). From these figures one can conclude that our figures are high.

Although it is hard to find the exact reason for these differences, two main sources for the differences have been identified. The first is that the conversion efficiency for electricity from primary sources is a European average, while other research is often based on a single country. For example, BUWAL refers to the Swiss situation where electricity is produced more efficiently than the European average. The second reason is that the caloric values for roundwood we calculated are based on European species-use averages while species-use in a single country can differ from that average. Moreover, the results of our research are difficult to compare with others because of the definition used for recycling. RPU rates refer to inputs, while other research refers to outputs.

The non-linear relationship we found results in approximately 5 GJ/t lower reduction potentials than when a linear relationship is assumed. In our research the maximum energy savings that can be achieved are 8.2 GJ/t (-16.9%) for chemical paper and 5.3 GJ/t (-11.4%) for mechanical paper. These figures are in general lower than other researches conclude (e.g. (Morris 1996) finds energy savings in the range of 14 – 39
Because the non-linear relationship explains only a part of the difference, other factors need investigation.

### 4.6.6. Conclusions

Our research shows that a non-linear relationship exists for paper recycling due to higher average fibre turnover rates at higher recycling rates. Moreover, non-linearity leads to an optimum recycling rate. However, the optimum can in general be found at high recycling rates. Therefore our research concludes that recycling is in general the more energy efficient option rather than incineration, which is in line with previous research (IIED 1996). However, the non-linear relationship between waste paper recycling and virgin fibre requirements results in lower potential energy savings than if there were no fibre damage.

Total external supply of energy (the grey areas in Figure 4.4) is a proxy indicator for CO₂ emissions because electricity production is largely based on carbon-intensive fossil fuels. Therefore our research suggests that increasing recycling rates increases CO₂ emissions for the chemical process. This is in line with previous research mentioned in the introduction (IIED 1996). On the other hand, our research concludes that increasing recycling rates decreases CO₂ emissions for the mechanical process (contrary to previous research). However, it should be noted that the previous studies mentioned in the introduction often focus solely on the chemical pulping processes.

<table>
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<tr>
<th>Key findings</th>
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</thead>
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<td>· Waste paper recycling is more energy efficient than waste paper incineration.</td>
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<td>· The benefits of recycling tend to suffer from diminishing returns.</td>
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<tr>
<td>· Recycling affects the over-all resource mix of paper production: increasing recycling results in increasing use of non-renewable resources and decreasing use of renewable resources.</td>
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### 4.7. Acknowledgements

Irene Edel, Laurie Hendrickx, Sander Lensink, Gert-Jan Nabuurs, Sanderine Nonhebel, Anne Jelle Schilstra, Ton Schoot Uiterkamp, and the anonymous reviewers of the *Journal of Industrial Ecology* are acknowledged for their contributions to this Chapter.
4.8. Appendix A: Solutions of the substance flow model with different numbers of stocks

The Equations corresponding to the model (N=4) as presented in Figure 4.1 are:

\[ z = F_1 + F_2 + F_3 + F_4 + F_8 \]
\[ F_1 = S_1' (1 - x) \]
\[ F_2 = S_2' (1 - x) \]
\[ F_3 = S_3' (1 - x) \]
\[ F_4 = S_4' (1 - x) \]
\[ F_5 = S_1' x \cdot y \]
\[ F_6 = S_2' x \cdot y \]
\[ F_7 = S_3' x \cdot y \]
\[ F_8 = S_4' x \cdot y \]
\[ S_1 = \int z - F_1 - F_5 \]
\[ S_2 = \int F_5 - F_2 - F_6 \]
\[ S_3 = \int F_6 - F_3 - F_7 \]
\[ S_4 = \int F_7 - F_4 - F_8 \]
\[ \Sigma S = S_1 + S_2 + S_3 + S_4 \]

In dynamic equilibrium the stocks (S_1-S_4) are constant and therefore the integrals above can be rewritten as:

\[ z = F_1 + F_5 \]
\[ F_5 = F_2 + F_6 \]
\[ F_6 = F_3 + F_7 \]
\[ F_7 = F_4 + F_8 \]

In this appendix, we show how algebraic solutions of the equations corresponding to the model as presented in above are generalized in formula n. However, we do not give proof. First, solutions for N=1, N=2, and N=3 are shown; next a general solution is shown.

Let N be the number of stocks, x is the recycling rate (RPU), y is the damage rate, and z is the virgin fibre requirement,

Let \( S_{\text{tot},N} = \sum_{i=1}^{N} S_i \), i.e. the total fibre in stocks.

Then, for N=1:

\[ z = (1 - x) \cdot S_1 + xy \cdot S_1 = (1 - x + xy) \cdot S_1 \]  \hspace{1cm} (a)

And:

\[ S_{\text{tot},1} = S_1 \]  \hspace{1cm} (b)

106 “x” and “y” below are model input variables and the value of “z” in dynamic equilibrium is the model output.

x = recycling rate; y = damage rate; z = new fibre requirement.
Therefore, substituting $S_1$ in (a) from (b) gives:
\[ z = S_{tot,1} (1 - x + xy) \]  \hspace{1cm} (c)

Then, for N=2:
\[ S_1 \cdot (xy) = S_2 \cdot (1 - x + xy) \Rightarrow S_2 = S_1 \cdot \frac{xy}{1 - x + xy} \]  \hspace{1cm} (d)

And:
\[ S_{tot,2} = S_1 + S_2 \]  \hspace{1cm} (e)

Therefore:
\[ S_{tot,2} = S_1 + S_1 \cdot \frac{xy}{1 - x + xy} \Rightarrow S_1 = S_{tot,2} \left(1 + \frac{xy}{1 - x + xy}\right)^{-1} \]  \hspace{1cm} (f)

And since formula (a) is valid for every value of N is integer:
\[ z = S_{tot,2} \cdot \frac{1 - x + xy}{1 + \frac{xy}{1 - x + xy}} \]  \hspace{1cm} (g)

Then, for N=3:
\[ S_1 \cdot (xy) = S_2 \cdot (1 - x + xy), S_2 \cdot (xy) = S_3 \cdot (1 - x + xy) \]
\[ \Rightarrow S_2 = S_1 \cdot \left(\frac{xy}{1 - x + xy}\right), S_3 = S_2 \cdot \left(\frac{xy}{1 - x + xy}\right) \]  \hspace{1cm} (h)

And:
\[ S_{tot,3} = S_1 + S_2 + S_3 \]  \hspace{1cm} (i)

Therefore:
\[ S_{tot,3} = S_1 + S_1 \cdot \left(\frac{xy}{1 - x + xy}\right) + S_1 \cdot \left(\frac{xy}{1 - x + xy}\right)^2 \]
\[ \Rightarrow S_1 = S_{tot,3} \cdot \left(1 + \left(\frac{xy}{1 - x + xy}\right) + \left(\frac{xy}{1 - x + xy}\right)^2\right)^{-1} \]  \hspace{1cm} (j)

And since formula (a) is valid for every value of N is integer:
\[ z = S_{tot,3} \cdot \frac{1 - x + xy}{1 + \left(\frac{xy}{1 - x + xy}\right) + \left(\frac{xy}{1 - x + xy}\right)^2} \]  \hspace{1cm} (k)

Then, for N:
\[ S_{N-1} \cdot (xy) = S_N \cdot (1 - x + xy) \]
\[ \Rightarrow S_N = S_{N-1} \cdot \left(\frac{xy}{1 - x + xy}\right)^{N-1} = S_1 \cdot \left(\frac{xy}{1 - x + xy}\right)^{N-1} \]  \hspace{1cm} (l)

And:
\[ S_{\text{tot},N} = \sum_{i=1}^{N} S_i \Rightarrow \sum_{i=1}^{N} S_i = S_1 \cdot \sum_{i=0}^{N-1} \left( \frac{xy}{1-x+xy} \right)^i \]

\[ \Rightarrow S_1 = S_{\text{tot},N} \cdot \left( \sum_{i=0}^{N-1} \left( \frac{xy}{1-x+xy} \right)^i \right)^{-1} \]

Therefore:

\[ z(x) = \sum_{i=1}^{N} S_i \cdot \frac{1 - x + xy}{\sum_{i=0}^{N-1} \left( \frac{xy}{1-x+xy} \right)^i} = \frac{S_{\text{tot},N} \cdot (x-1)}{\left( \frac{xy}{1-x+y} \right)^N - 1} \]
Values that have been changed to perform the sensitivity analysis are underlined. The upper parts of the tables are input variables; below the line are model outputs.

N = the number of times fibres are damaged and then reused; y = damage rate; RWE = roundwood equivalents; LHV = lower heating value

Table 4.5: Chemically processed paper

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Optimal (%) 93.3% 100% 82.3% 84.3% 93.3% 82.4% 100% 92.5% 66.7% 100% 87.4% 94.5% 92.0%

Maximal (GJ/t) 48.5 48.5 45.0 48.5 44.4 65.7 48.5 48.5 40.3 56.7 48.3 48.6 47.8 49.2

Minimal (GJ/t) 40.3 37.0 43.4 39.4 40.3 39.3 43.6 35.9 40.5 37.9 41.9 39.7 40.5 39.2 41.4

Possible reduction with recycling 16.9% 23.8% 10.6% 12.4% 16.9% 11.6% 33.7% 26.0% 16.6% 6.0% 26.2% 17.9% 18.1% 15.8%

10% lower recycling +0.3% +0.5% +0.2% +0.3% +0.3% +2.0% +1.2% +0.3% +0.2% +1.0% +0.6% +0.3% +0.3% +0.3%

10% higher recycling +0.3% +0.2% +0.3% +0.3% +0.2% +0.3% +0.2% +0.3% +0.3% +0.2% +0.3% +0.3% +0.3% +0.3%

Table 4.6: Mechanically processed paper

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Optimal (%) 80.9% 91.3% 66.0% 23.9% 100% 78.7% 82.9% 84.7% 75.0% 64.1% 92.2% 93.1% 76.2% 77.2% 84.2%

Maximal (GJ/t) 46.5 46.5 46.5 45.8 47.3 46.5 46.5 42.0 51.1 46.4 46.6 44.1 49.0

Minimal (GJ/t) 41.2 38.2 44.0 37.0 43.4 41.0 41.4 40.5 42.2 39.7 42.4 41.0 41.3 39.6 42.8

Possible reduction with recycling 11.4% 18.0% -5.5% -7.1% -22.5% -10.5% -12.3% -12.9% -9.3% -5.5% -17.0% -11.8% -11.4% -10.2% -12.6%

10% lower recycling +0.3% +0.3% +0.2% +0.1% +0.5% +0.2% +0.3% +0.2% +0.3% +0.3% +0.2% +0.3% +0.3% +0.3% +0.3%

10% higher recycling +0.3% -n/a +0.2% +0.1% -n/a +0.3% +0.3% +0.3% +0.3% -n/a +0.3% +0.3% +0.3% +0.3% +0.3%