Discussion on EMERGY Allocation in Joint Production and Wastes

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ABSTRACT

The objective of this paper is to discuss several methods of EMERGY allocation in joint production and to present an approach for dealing with wastes (a form of joint production) within the framework of EMERGY analysis.

Biophysical or economic criteria are often considered in the allocation of joint-products. Several biophysical and economic weights for this are discussed, including the conventional EMERGY approach, EMERGY fractions, energy/exergy weights and economic value, and their effects on final result.

This analysis was illustrated by a case study of the Portuguese eucalyptus pulp industry. To calculate the EMERGY of wastes, the energy needed by nature to absorb them should be used. In this case, the analysis is made downstream, instead of upstream, i.e., wastes’ EMERGY should be allocated to the products of the activity that produces them. This approach sheds a favorable light on industries that recycle (i.e., using wastes as their resources), because they are using zero EMERGY resources.

INTRODUCTION

According to Guinée et al. (2004) joint production is defined as a unit process yielding two or more flows constituting the goal of this unit process (also called functional flow). In a unit process, three situations may occur: the existence of two or more functional outflows without any functional inflow, co-production, where there is the production of two useful outputs and where the inputs are not the goal of the process; the existence of no functional outflow but more than one functional inflow – wastes processing, where the goal of the process is to treat the inputs, i.e. wastes; or the existence of more than one functional inflows and more than one functional outflows – recycling process, where the goal is to treat wastes in the form of inputs and to produce a useful product.

Allocation of joint-products has raised discussion, especially among life cycle analysts (see for instance Guinée et al., 2004, and Weidema and Norris, 2002), on how impacts on emissions and resource depletion are allocated to each co/by-product. Several approaches have been created such as partitioning according to mass, energy or economic values and substitution (avoided processes are subtracted from the process flows).

Ayres (2004) refers to EMERGY, as well as many other methods of analysis, as having difficulty in practice dealing with joint outputs. This paper presents a summarized discussion on several approaches to joint production, including the EMERGY approach.

Wastes can be defined as a below zero economic value flow (Guinée et al., 2004). EMERGY, as many other methods, handles wastes by considering the inputs to the ‘end of pipe’ treatment processes inside the economy; that is, after pollution is generated, the EMERGY used to clean emissions or minimize the wastes impacts on environment is calculated. The effects of wastes on environment, in general, are not accounted for. They can be determined by calculating the EMERGY related to the environmental impacts verified. For instance, the EMERGY of emissions to the environment generating
acid rain (e.g. sulphur dioxide, SO₂) can be determined through the calculation of the EMERGY of the plants destroyed by the acid rain. However in practice, this is not usually done.

To effectively provide information for decision-makers and lead to possible changes in the systems analyzed, EMERGY analysis must be able to provide answers to some important some questions, such as where to act within the economic structure of the system. EMERGY is quite silent about this by not allocating the EMERGY of wastes to whom is responsible for them, and instead analyzing the system as a whole. Although there is much literature on internalizing externalities into the production processes (e.g. Bastianoni et al., 2001), intermediate transformities (those used to determine the system’s EMERGY flows) do not incorporate these externalities (for instance the transformities for fossil fuels do not include the impacts for land occupation, or the impacts of an eventual oil spill).

The structure of this paper is as follows: first, we discuss the problem of allocation of joint production; then we present a discussion on how to consider wastes in EMERGY analysis; and finally we report on the application of two approaches for joint production in EMERGY analysis for the case study of the Portuguese eucalyptus pulp industry: conventional EMERGY analysis (Equation 1) and the energy/exergy value weighting approach (Equation 6).

**ALLOCATION IN JOINT PRODUCTION**

One unit operation can receive multiple mass or energy fluxes and it can produce more than one useful output flux (and also produce waste fluxes). In the situation of the production of more than one product, it is very difficult or impossible to determine the inputs’ fractions that are related to each of the joint products, creating the problem of determining the unknown \( \hat{i}_x \) and \( \hat{i}_y \), respectively by the transformities of joint products \( x \) and \( y \) (see Figure 1a).

![Figure 1](image)

*Figure 1.* (a) Simplified joint production process with two inputs and two outputs. (b) Separate production of the two products in (a).
To solve this allocation problem EMERGY analysis assigns the total EMERGY (of inputs) to each product:

\[
\hat{t}_x = \frac{\hat{B}_{xy}}{E_x}, \quad \hat{t}_y = \frac{\hat{B}_{xy}}{E_y},
\]

(1)

where \(E_x\) and \(E_y\) are the energies of joint products \(x\) and \(y\), respectively, and \(\hat{B}_{xy}\) is the EMERGY of inputs \(i\) and \(ii\) (\(\hat{B}_{xy} = B_{xy(i)} + B_{xy(ii)}\)). These equations lead to a total output EMERGY that is higher than the total input EMERGY, i.e., total EMERGY is non-additive with respect to joint-products (EMERGY rule #4, Brown and Herendeen, 1996). This complicates both calculation and analysis and Bastianoni and Marchettini (2000) state that it can lead to the precipitate conclusion that joint-production is not feasible when compared to the production of only one output. Bastianoni and Marchettini (2000) introduce new EMERGY based indices, to help analyze complex joint-production systems. These are the joint transformity, \(\hat{t}_{xy}\),

\[
\hat{t}_{xy} = \frac{\hat{B}_{xy}}{E_x + E_y}
\]

(2)

and the weighted average of transformities, \(\bar{t}_{xy}\),

\[
\bar{t}_{xy} = \frac{E_x}{E_x + E_y} t_x + \frac{E_y}{E_x + E_y} t_y = \frac{B_x + B_y}{E_x + E_y},
\]

(3)

where \(t_x\) and \(t_y\) are, respectively, the transformities of \(x\) and \(y\) when produced separately (separate production); and \(B_x\) and \(B_y\), the EMERGIES of separate production of products \(x\) and \(y\) (see Figure 1b), independent of the system under analysis. Joint-production is better than separate production if, and only if, \(\hat{t}_{xy} < \bar{t}_{xy}\), i.e. \(B_{xy} B_x + B_y\) (note, however, that either separate production or co-production may not be possible). This is a good indicator to help in the conclusion about the efficiency of joint-production, compared to output’s separate production. However, it does not solve the problem of the complexity of calculation and analysis.

Avoiding Allocation in Joint Production

EN ISO 14041 (1998) presents, as a first approach to deal with joint-production, the expansion of system boundaries to vary the amount of each co-product while holding constant all the other products’ amounts (Azapagic and Clift, 1994; Fleischer, G., 1994; Finnveden, G., 1994; and Ekvall, T., 1994). Expanding system boundaries allows consideration of all relevant joint-products.

System expansion, however, does not solve the problem for processes where the ratio of joint-products is necessarily fixed, leading to the need of allocation. Weidema and Norris (2002) refer to system boundary expansion as a more general theory, while allocation in joint-production is seen as a particular case of system boundary expansion. However, in this paper, the two approaches (system boundary expansion and allocation) are treated separately.

EMERGY Values Weighting Approach

Another approach is the use of EMERGY values as weighting factors for the separate production of each of the joint-products:

\[
\hat{B}_x = \frac{B_x}{B_x + B_y} \hat{B}_{xy}, \quad \hat{B}_y = \frac{B_y}{B_x + B_y} \hat{B}_{xy}.
\]

(4)
This approach considers the separate production of products $x$ and $y$. It has complex computation since it requires data on the separate production of the joint-products (which may not be available) and their EMERGY value.

**Economic Values Weighting Approach**

Another approach discussed in EN ISO 14041 (1998), and largely used in life cycle analysis (LCA), is to use economic values as weighting factors. This approach considers the economic value created by a process as the driver of that process, and it uses allocation factors based on joint-products’ prices (Guinée et al., 2004).

The advantages of such a method are that a greater fraction of resources and emissions (environmental impacts) are allocated to products with greater market value; hence the cost of a given product incorporates a proportional responsibility to the environment.

The inconvenience of this approach is that it incorporates human preferences (which are somehow against biophysical principles) and that other allocation procedures must be used when analyzing natural systems, where the economic price is zero.

**Energy/Exergy Values Weighting Approach**

The fourth approach considered is to use energy (Finnveden, 1994; Ekvall, 1994) or exergy as a weighting factor (other biophysical properties could be employed such as mass, molar content, volume or area). The energy allocation procedure is given by:

$$
\hat{B}_x = \frac{E_x}{E_x + E_y} \hat{B}_{xy}, \quad \hat{B}_y = \frac{E_y}{E_x + E_y} \hat{B}_{xy}.
$$

Using energy as a weighting factor, one can redefine transformities, $\tilde{t}$, as the total EMERGY of a process divided by its total energy. These redefined transformities are equal to the joint transformities defined by Bastianoni and Marchettini (2000), where these redefined transformities are used for the total EMERGY computation, and not as a mere indicator. Therefore,

$$
\tilde{t}_{xy} = \tilde{t}_y = \frac{\hat{B}_{xy}}{E_x + E_y}, \quad \hat{B}_x = E_x \tilde{t}_x, \quad \hat{B}_y = E_y \tilde{t}_y.
$$

$\tilde{t}_x$ is equal to $t_x$ when there is no co-production. With this approach there is no need to use separate production values to evaluate joint-production and these ‘redefined transformities’ from joint-products are equal (as in usual energy analysis), so allocation becomes very simple (joint-products and splits are treated in the same way). Also, the problem of double counting is eliminated since joint-products’ impacts (on resources or emissions) can be summed.

**WASTES IN EMERGY ANALYSIS**

Waste has been defined as a below zero economic value flow (Guinée et al. 2004). EMERGY, as well as many other methods, handles wastes by considering the inputs to the ‘end of pipe’ treatment processes inside the economy to minimize the wastes’ impacts on the environment. Wastes emitted to the environment, and their effects on it, are not considered.

Allocation in waste treatment processes, from our point of view, should give responsibility for waste treatment or its environmental burdens to producers of a product or service, and so wastes’ treatment EMERGY should be allocated to these producers.

Figure 2 presents a generic economic operation, producing wastes. The economic operation receives from the environment products and services (ecological services) and, from the economy other products (the latter are not presented in Figure 2). Three major processes with respect to wastes...
production can occur: treatment operations in economic systems; recycling within economic systems; and emissions to the environment. The first and the second are the ‘end of pipe’ processes.”

Consider first the effect of treatment on wastes’ EMERGY. Wastes’ EMERGY is zero when emitted from a production process. It might be considered that EMERGY of wastes would be acquired in treatment operations through the inputs needed for the treatment operation. However, treatment operations transform wastes into other wastes. Hence, the EMERGY acquired by wastes in treatment operations should be allocated to the useful product, whose production process originally produced the wastes. Hence, wastes always have zero EMERGY. The useful product’s EMERGY is then the sum of its productive EMERGY plus the EMERGY of its waste treatment operations.

Consider now recycling within the economic system. A recycling operation is a productive process that transforms wastes into market-valued resources. Hence, zero EMERGY wastes are transformed into new resources with an EMERGY equal to the EMERGY of the recycling process, i.e. the EMERGY of the recycled product is equal to the EMERGY of the recycling process, calculated as a general operation.

Consider now the emissions to the environment (note that all treatment and recycling operations emit wastes to the environment, besides those wastes emitted directly to the environment without any treatment, e.g. CO₂). Emissions are analyzed by considering wastes’ assimilation by nature through a virtual process of transforming them into new economic resources. To track the passage of wastes through the environment, one of two approaches can be followed:

- Choose the most probable passage of wastes through the environment, till they became a market valuable resource; or
- Choose a virtual process of natural assimilation, considering that this process occurs for the wastes considered (similar to the approach for wastes taken by the Ecological Footprint method, Wackernagel and Rees, 1998).

For processes occurring in the environment it is possible to consider natural production processes where the inputs are wastes and the outputs are market-valued resources. The emery of the...
natural processes used to assimilate the wastes (as in the case of waste treatment within economic systems) must be allocated to the main product that created the waste in first place. For example, in Figure 3 the same economic activity is presented with two different system boundaries. Considering the first boundary (figure 3a), CO$_2$ would have an EMERGY value equal to pulp’s, since they are joint products. CO$_2$ emitted is then sequestered by forests, producing new wood, but this process is not considered in the analysis using the boundary in Figure 3a. Considering the second boundary (Figure 3b, CO$_2$ and pulp still have the same EMERGY value, but CO$_2$ sequestration by forests is now also included. In this situation it is easier to see that the system has an output (wood) that is equal to one of its inputs. However, they would have different EMERGY values since they come from different processes.

If we consider the concept of avoided environmental burdens, the economic activity is producing an output that can substitute an input (for instance, wood as fuel), and thus, this concept would indicate that the EMERGY of the input (wood as fuel) should be subtracted from the main product’s (in this case, pulp) EMERGY. Doing so, we are benefiting the economic activity due to the fact that it produces a useful output (although indirectly).

Since the production of the new resource using waste emissions avoids the use of raw environment resources, this should be counted in favour of the economic system.

There are two problems with this approach: persistent pollutants and energy wastes (heat). Heat release to the environment is an irreversible process increasing entropy, and this matter must be further investigated.

![Diagram](image)

**Figure 3.** The same economic activity analyzed with two different system boundaries, where system (a) is contained in system (b). The system boundaries are depicted by dashed rectangular boxes. The dashed arrow depicts a process occurring in nature (outside the economic system).
CASE STUDY FOR ALLOCATION WITH A JOINT-PRODUCT: PORTUGUESE EUCALYPTUS PULP PRODUCTION

This section uses the example of the Portuguese eucalyptus pulp production to compare two approaches for analyzing joint-products: conventional EMERGY analysis (Equation 1) and the energy/exergy value weighting approach (Equation 6).

Using the energy/exergy value weighting approach, EMERGY algebra is changed, thus it is necessary to recalculate all transformities published up to now according to the new algebra. For the redefinition of the transformities it is necessary to go upstream in the energy fluxes, back to the solar energy from the sun contribution. Solar energy arriving on Earth from the Sun is split (Oort and Peixoto, 1992; Smil, 1991); about 20% is absorbed by the atmosphere and is used for wind generation and other atmospheric processes. Land and oceans capture 50% of solar radiation. The remaining 30% is sent back to space by clouds, dust and the earth’s surface reflection.

However, as a simple example to compare the results and effects of using different approaches in analyzing joint-production, conventional EMERGY analysis (Equation 1) was used for calculating the EMERGY of inputs. The EMERGY of outputs was determined using both approaches: conventional EMERGY analysis (Equation 1) and the energy/exergy values weighting approach (Equation 6). Results are presented in Table 1.

The pulp industrial process has two products, pulp and electricity (obtained through cogeneration), making it a good example for illustrating allocation in joint-products. The EMERGY diagram for pulp production is presented in Figure 4. Data on eucalyptus pulp production can be found in Table 1, which reports averages obtained from Portuguese producers. Notes to Table 1 can be found in the Appendix.

In the joint-production scenario conventional EMERGY analysis allocates the total EMERGY of 2.61x10^17 seJ to both pulp and electricity, yielding transformities of 3.41x10^4 seJ/J and 6.59x10^5 seJ/J, respectively.

Figure 4. EMERGY diagram of Portuguese eucalyptus pulp production.
Table 1. EMERGY Contributions to Pulp Production (Figure 4), considering the production of 1000 ton of printing and writing paper.

<table>
<thead>
<tr>
<th>Note</th>
<th>Inputs and Units</th>
<th>Inflow (Units/FU)</th>
<th>Emergy/Unit (seJ/unit)</th>
<th>Emery (E16 seJ/FU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Euc. prod:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Direct Solar Radiation, J</td>
<td>2.17E+14</td>
<td>1.00E+00</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>Rain, g</td>
<td>6.40E+11</td>
<td>1.28E+05</td>
<td>8.19</td>
</tr>
<tr>
<td>3</td>
<td>Net mineral topsoil loss, g</td>
<td>2.31E+04</td>
<td>1.68E+09</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>Fuel, J</td>
<td>6.13E+10</td>
<td>6.60E+04</td>
<td>0.40</td>
</tr>
<tr>
<td>5</td>
<td>Coal, J</td>
<td>4.91E+06</td>
<td>5.71E+04</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>Natural Gas, J</td>
<td>8.19E+07</td>
<td>5.71E+04</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>Nitrogen (from fertilizer), g</td>
<td>1.99E+06</td>
<td>2.41E+10</td>
<td>4.79</td>
</tr>
<tr>
<td>8</td>
<td>Phosphate (from fertilizer), g</td>
<td>5.80E+04</td>
<td>2.20E+10</td>
<td>0.13</td>
</tr>
<tr>
<td>9</td>
<td>Potash (from fertilizer), g</td>
<td>0.00E+00</td>
<td>1.74E+09</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td><strong>Transport:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Fuel, J</td>
<td>5.21E+9</td>
<td>6.60E+04</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td><strong>Pulp prod:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Water, g</td>
<td>2.75E+10</td>
<td>1.28E+05</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>Fuel, J</td>
<td>8.94E+11</td>
<td>6.60E+04</td>
<td>5.90</td>
</tr>
<tr>
<td>13</td>
<td>Chemicals, g</td>
<td>9.92E+07</td>
<td>6.38E+08</td>
<td>6.33</td>
</tr>
<tr>
<td>14</td>
<td>Total</td>
<td></td>
<td></td>
<td>26.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Output (Units/FU)</th>
<th>Transformity using conventional Method (Total EMERGY / Output)</th>
<th>Transformity using Energy/Exergy Weighting approach (Total EMERGY*output/total output)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Pulp, J</td>
<td>7.66E+12</td>
<td>3.41E+04</td>
</tr>
<tr>
<td>16</td>
<td>Co-generated Electricity (kWhr)</td>
<td>3.97E+11</td>
<td>6.59E+05</td>
</tr>
</tbody>
</table>

Abbreviations: seJ = solar emJoules; yr = year; E16 means multiplied by 10^16; FU = functional unit, 1000 tones of printing and writing paper, correspondent to 610 ton of pulp.

Now, let us consider the energy/exergy weighting approach (Equation 6). Results show a ‘redefined transformity’ of 3.24x10^4 seJ/J for both pulp and co-generated electricity. This value is lower than that obtained by conventional EMERGY analysis (Equation 1) for pulp (3.41x10^4 seJ/J) and electricity (6.59x10^5 seJ/J). EMERGY values for pulp and electricity, using the energy/exergy weighting approach (Equation 6), are 2.48x10^17 seJ and 0.13x10^17 seJ, respectively. The sum of these values is equal to total EMERGY by using the conventional EMERGY approach (Equation 1), 2.61x10^17 seJ. Electricity is allocated with a lower EMERGY content using the energy/exergy weighting approach (Equation 6) due its lower energy content.

The energy/exergy weighting approach (Equation 6) presents different results than the conventional EMERGY analysis (Equation 1). Using the energy/exergy weighting approach (Equation 6), since pulp has higher energy content, more EMERGY is allocated to this output so that the transformity of both outputs are equal.
CONCLUSIONS AND FURTHER WORK

Two important points were discussed in this paper: allocation to joint-products, and the way that EMERGY handles wastes.

Several approaches for joint-production were referred to in this paper. All the approaches presented advantages and disadvantages when compared to each other. Different approaches lead to different results when analyzing a particular system.

For true joint-products, impacts (from resources or emissions) can be allocated using the conventional EMERGY analysis (Equation 1), EMERGY weights, economic weights, or energy/exergy weighting approach (Equation 6). If joint-products are not real joint-products, it is possible to vary the amount of one co-product holding all other output amounts constant, allowing the determination of the inputs’ impacts, for which each joint-product is responsible. Also, a change in joint-production allocation procedure leads to the need for the determination of new transformities for EMERGY.

In this paper an approach for wastes was presented as follows:

- All sources of EMERGY for a process should be assigned to the process’ useful output(s).
- Wastes are not considered useful outputs, so they have zero EMERGY value.
- The EMERGY from a waste treatment operation should be assigned to the product that originated the waste.
- Recycling operations are seen as productive operations, transforming wastes into new products. EMERGY from a recycling operation must be assigned to the new product produced.

Of the three situations analyzed for wastes, wastes emitted to nature are more complicated to analyze than recycling and waste treatment operations within economic systems. The proposal presented is to track wastes through the environment until they produce a new market-valued output, allocating their EMERGY to the product that generated the wastes in first place. This approach was not applied to the case study and needs further investigation.

Transformities and EMERGY values can be very different when different approaches are used for joint-production. This paper showed that using energy/exergy weighting approach (Equation 6) provides different results than conventional EMERGY analysis (Equation 1). However, for these new approaches to be applied in practice, further comparisons must be made between the different allocation procedures, and the methods for tracking wastes in the environment must be refined.

ACKNOWLEDGMENTS

We would like to thank Inês Azevedo, Nuno Cegonho and Tânia Sousa for their discussions on this paper. A special thanks to Ana Simões, for her interest and contributions. This work was supported by: POCTI under grant “General Theory of Sustainability and Application to Agriculture”, POCTI/MGS/47731/2002; and by FLAD under grant 631/03.

REFERENCES

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APPENDIX

Notes to Table 1

1. Direct Solar Radiation: Transformity = 1 seJ/J (Odum 1996); Average Annual Insolation = 6.49E+09 J/m2 (between 140 and 155 kcal/m2, Instituto do Ambiente, 2003); Area = 2.3E+04 m2 (obtained from mass wood logs from Portuguese industries, using eucalyptus productivity obtained from Globulus 2.1); a 30% albedo was considered; Sun energy = 2.17E+14 J.

2. Rain: EMERGY/mass = 128000 seJ/g (Odum, 1996 corrected by a factor of 1.68); Water needs (consumption from rain) = 6.40E+11 g (Sequeira per. com., considering 700 mm as the ideal precipitation for eucalyptus, we have 0.7 m3/m2, the area needed to produce eucalyptus for 1000 ton paper is 9.14E+05, according to the eucalyptus density of 1667 trees/ha). Using a density of 1000 kg/m3 it is possible to obtain the mass of water needed for eucalyptus plantations.

3. Net mineral topsoil loss: Soil, Mineral Fraction = 1.68 E+09 seJ/g (Odum, 1996 corrected by a factor of 1.68); Nutrients loss = 23 135.65 g (nutrients lost are K2O5 and CaO, from a nutrients balance for common fertilization practices – values presented in the table; leaching values – obtained from Cortez 2000; and eucalyptus chemical composition obtained from the model Globulus 2.1, developed by Instituto Superior de Agronomia; the procedure for the calculation was described by Vieira, 2002).

4. Fuel: Transformity = 66000 seJ/J (Odum, 1996 corrected by a factor of 1.68, Odum et al., 2000); Crude Oil mass = 1463.77 kg (from fertilizer use, obtained from Salgueiro et al. 1996, and machinery use in eucalyptus production, with data obtained from SimaPro 4.0); Specific energy = 44000 kJ/kg (http://www.wec.ankara.edu.tr/wec/enersour.html); Energy from Crude Oil = 6.13E+10 J.

5. Coal: Transformity = 57120 seJ/J (Odum, 1996 corrected by a factor of 1.68, Odum et al., 2000); Coal mass usage = 0.17 kg (indirect input from machinery use in the eucalyptus production, data from SimaPro 4.0 software); Specific Energy = 29300 kJ/kg (http://www.wec.ankara.edu.tr/wec/enersour.html); Coal energy = 4.91E+06 J.

6. Natural Gas: Transformity = 80640 seJ/J (Odum, 1996 corrected by a factor of 1.68, Odum et al., 2000); Natural Gas consumption = 2.03 kg (indirect input from machinery use in the eucalyptus production, data from SimaPro 4.0 software); Volume Energy = 38100 kJ/m3 (http://www.wec.ankara.edu.tr/wec/enersour.html); Specific energy = 0.94 kg/m3; Specific Energy = 40370 kJ/kg; Natural Gas Energy = 8.19E+07 J.

7. Nitrogen: Emergy/mass = 2.41E+10 seJ/g N (Brandt-Williams, 1999); Nitrogen consumption = 1.98E+06 g (from fertilizer used, amount of fertilizer known from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002).

8. Phosphate: Emergy/mass = 2.20E+10 seJ/g P (Brandt-Williams, 1999); Phosphorus consumption = 5.80E+04 g (from fertilizer used, amount of fertilizer known from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002).

9. Potash: Emergy/mass = 1.74E+09 seJ/g K (Brandt-Williams, 1999); Potash consumption = 0 g (from fertilizer used, amount of fertilizer known from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002).

10. Fuel: Energy from Crude Oil = 1.99E+12 J, obtained from Simaprox 4.0. 6.01E+04 ton.km = [(total mass to be transported to pulp mill= 1.21E+03 ton)x(50km/trip) + (return of empty truck = 0 ton for 50 km)].
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11 Water: $2.74\times 10^{10}$ g (from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002).

12 Fuel: Crude Oil = 21351.05 kg (from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002); Energy from Crude Oil = $8.94\times 10^{11}$ J.

13 Chemicals: Emergy/mass = $6.38\times 10^{8}$ sej/g (Ortega, 1998); Chemicals consumption = $9.92\times 10^{7}$ g (from inquiries made to Portuguese producers; a detailed description can be found in Vieira, 2002).

14 Equal to the sum of inputs 2 to 13. The sun’s EMERGY was not included to avoid double counting (the sun’s EMERGY is lower than the EMERGY from the rain chemical potential).

15 Pulp: to produce 1000 ton of paper 610 ton of pulp is needed (data on production obtained from inquiries made to Portuguese pulp industries, a detailed description can be found in Vieira, 2002). A specific energy of 12560 kJ/kg (http://www.wec.ankara.edu.tr/wec/enersour.html) was used for energy calculation. The redefined transformity is calculated with equation 7.

16 Electricity: in the production of 610 ton of pulp there is the production of $1.10\times 10^5$ kWh (data on production obtained from inquiries made to Portuguese pulp industries; a detailed description can be found in Vieira, 2002). Energy determined according to $1.10\times 10^5$ (kWhr. = kJhr./sec) * 1000 (J/kJ) * 60 (min./hr.) * 60 (sec/min). Redefined transformity is determined according to equation 7.