Life-cycle thinking in the pulp and paper industry, Part I: Current practices and most promising avenues

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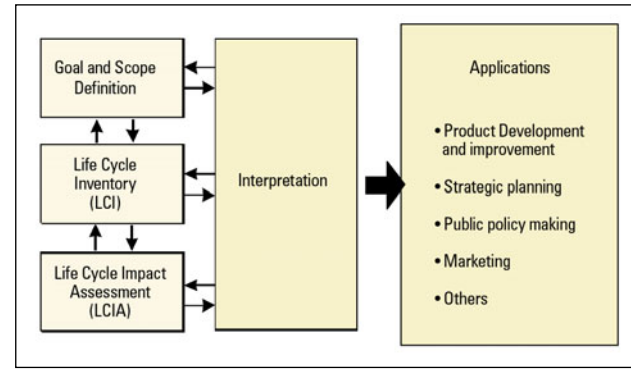
ABSTRACT: Life-cycle assessment (LCA) is a useful tool for analyzing the environmental burden of products at all stages of the life cycle. In this study, LCA applications in the pulp and paper industry were reviewed and classified into six categories: comparison of products having the same function, identification of "hot spots," comparison of process technical options, comparison of waste management options, evaluation of new products, and strategic planning and evaluation. The most sensitive application to the subjective elements of LCA is the comparison of products with the same function, for example, the comparison of paper-based and polystyrene-based egg packaging. We found that process analyses, comparisons of process options, and comparisons of end-of-life scenarios have been performed most extensively. Because of the growing interest in environmentally conscious manufacturing, the pulp and paper industry has begun to expand its regulatory based environmental management systems to include a continuous improvement orientation. Evaluation of new products has not been reported as a major application of LCA thus far. Although only a few LCA studies related to strategic evaluation are available, this is increasingly being considered as a promising future area for LCA application.

Application: This publication provides a survey of LCA applications in the pulp and paper industry.

LCA is a tool to analyze the environmental burden of products at all stages of their life cycle: from the extraction of resources to final disposal. The International Organization for Standardization (ISO) defines four major steps in the LCA methodology, summarized in **Fig. 1**.

The reason for performing the LCA study, the audience, and the methods are described in the goal and scope definition. In the inventory phase, the inputs and the outputs across the product cycle are compiled and quantified. In the impact assessment phase, the magnitude and importance of the potential environmental effects are evaluated. Finally, in the interpretation phase, the results of inventory and impact assessments are combined and related to the goal and scope to obtain conclusions and to develop valid recommendations.

LCA is a developing methodology with limitations on its use. Several main challenges have been identified. The first concerns the inventory stage and the effort required to obtain precise, accurate, and valid data across the product chain. Another is related to the impact assessment stage. Some impact categories, especially those related to local impacts, are still under development. From a pulp and paper perspective, it is important to note that land use is an important impact category, but there is still a lack of consensus on methods for quantifying it. Many characterization methods do not quantify resources well, preventing the assessment of renewable resources in LCA studies. The important effect of carbon sequestration into paper products is not accounted for explicitly in studies, a matter addressed in [1].



1. LCA framework.

OBJECTIVES AND METHODOLOGY

The objectives of Part I of this paper are: a) to survey LCA applications in the pulp and paper industry, and b) to outline the strengths and weaknesses of different LCA applications through critical analysis.

LCA APPLICATIONS

Fields of application

Forty studies published between 1990 and 2005 were reviewed to develop an overall picture of LCA applications in

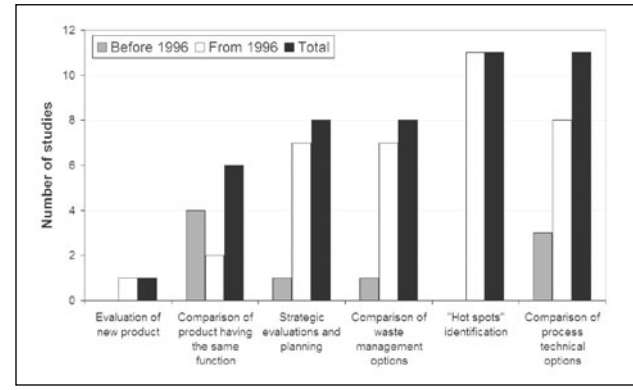
	REFERENCE	OBJECTIVES	MAIN CONCLUSIONS
Paper vs. Plastic Bags	Franklin Associates 1990 [2] United States	Comparison of paper and polyethylene (PE) bags in the United States, using resource and environmental profile analysis (REPA) or life-cycle inventory (LCI).	– Energy requirements are generally less for PE bags. – At all recycling rates: • PE bags generate less solid waste; • Atmospheric and water emissions are lower for PE bags.
	Eurosac 1993 [3] France	Comparison of industrial paper and PE bags.	– Paper bags are better from the following standpoints: • fossil energy use, global warming (GW), and smog. – PE bags are better from the following standpoints: • renewable energy consumption, chemical oxygen demand (COD), and water use.
	Sevitz 2002 [4] South Africa	Determination of the overall environmental impact of the life cycle of conventional plastic and paper bags in South Africa.	– Plastic bags have less environmental impact than paper bags for use ratios up to 2.5 plastic bags per one paper bag. – Paper becomes competitive only for high plastic- to paper-bag ratios. – The weighting method and assumptions used impact the results.
Paper vs. Cloth Diapers	Miljökonsult & Svensson 1993 [5] Sweden	Comparison of disposable and cloth diapers.	– With good laundry practices, cloth diapers contribute less to GW and acid rain and use less energy. – Disposable diaper manufacturing consumes significant amounts of fossil fuel. – Cloth and disposable diapers are difficult to compare due to the incompleteness of available information and the inability to weigh environmental effects against each other.
	Sauer et al. 1994 [6] United States	Assessment of the energy usage, water requirements, solid waste, atmospheric emissions, and water emissions generated by disposable and cloth diapers.	– Cloth diapers use more energy and water than disposable ones. – Disposable diapers generate more solid waste. – The authors stress that REPA should not be used to find a winner or a loser, but to identify possible improvements.
Others	Reichart & Hishier 2003 [7] Switzerland	Comparison of online, television, and newspaper information delivery, based on two different functional units.	– The choice of the best option depends on the functional unit used, but in each case it is possible to make recommendations concerning a better use of the media. – Using LCA is a good step toward increasing the knowledge of the environmental impact of different information media.
	Zabaniatou & Kassidi 2003 [8] Greece	Comparison of paper and polystyrene for egg packaging.	The application of the LCA methodology to polystyrene and recycled paper egg packaging does not provide a clear-cut answer as to which product is environmentally friendlier, but it seems that the polystyrene egg package has a higher environmental impact.

I. LCA applications for product comparison.

the pulp and paper industry. These studies can be classified into the following application fields:

- Comparison of products with the same function,
- Identification of "hot spots,"
- Comparison of process technical options,
- Comparison of waste management options,
- Evaluation of new products,
- Strategic planning and evaluation.

Figure 2 presents the breakdown of LCA studies by field of application (note that some studies fall into more than one field). LCA was originally designed for the comparison of products with the same function. However, since the publication of the first ISO standard on LCA (1996), it is increasingly being used for other applications.



2. Breakdown of LCA studies by field of application.

Comparison of products with the same function

LCA can be used for the comparison of paper products with alternatives having the same function. LCA has been used several times to compare paper with plastic bags and paper with cloth diapers, as shown in **Table I**. In addition, this table presents comparisons between online, television, and newspaper information delivery, and between paper and polystyrene egg packaging.

Product comparison is undoubtedly the LCA application most sensitive to subjective study assumptions. The reviewed

REFERENCE	OBJECTIVES	MAIN CONCLUSIONS
Eurosac 1993 [3] France	Assessment of the environmental burden of industrial paper bag manufacturing.	– The use of fossil energy and the emissions of CO_2 and SO_x are mostly linked to the production of energy. – Transport is the main source of NOx emissions.
Krokowski et al. 1999 [9] Sweden & Canada	Ecological evaluation of a typical newspaper and magazine along the paper cycle.	– Forest, energy, climate, water, and waste paper are the strategic factors in the evaluation of the paper cycle. – Processes upstream of the production of paper represent an important source of environmental impact. – LCA is a useful tool to identify the stages that cause most environmental impacts.
International Energy Agency 1999 [10] France	Development of a method for the assessment of the energy-related environmental impacts of paper products.	Energy-related impacts are mainly due to energy use in the mill, production of electricity, and production of fuels. Choice of system boundaries is therefore important.
Pajula et al. 2001 [11] Finland	Evaluation of the contribution of transportation to the overall environmental impact of the paper chain.	– CO_2, SO_2, and NOx are the emissions that are the most influenced by transport. – Paper production is the major contributor to CO_2 and SOx. – This result can change if non-fossil energy is used in the process.
Wiegard 2001 [12] Australia	Illustration of how LCA can be used to find opportunities for reducing GHG emissions.	Performing LCA for virgin and recycled pulp gave a good picture of mills in terms of GHG emissions.
Dias et al. 2002 [13] Lopes et al. 2003 [14] Portugal	Determination of process contributions to the life-cycle environmental impact of pulp and paper manufacture and use.	– Paper production is the dominant contributor to CO2 and SOx. – Pulp production is an important contributor to energy consumption and to eutrophication and acidification. – Transportation is the main emitter of NOx. – The disposal stage is assumed to make an important contribution to GW.
Pickin et al. 2002 [15] Australia	Evaluation of the GHG emissions along the Australian paper cycle.	One-half of GHG emissions from the paper cycle originate from landfilling of waste paper.
Sundin et al. 2002 [16] United Kingdom	Material and energy analysis for the paper cycle in the United Kingdom.	– Environmental benefits of reducing consumption of paper and improving technology are greater than those obtained from increasing recycling. – Modeling techniques and scenario-type sensitivity analyses are helpful for answering questions with a high level of complexity and uncertainty.
Windsperger et al. 2002 [17] Austria	Analysis of the importance of the environmental burdens associated with the upstream processes of paper production.	In many impact categories, the external processes, more specifically energy production, were at least as important as those on the production site.
Rehnström 2003 [18] Sweden	Understanding of the overall environmental impacts of black liquor recovery.	The chemical and energy inputs result in a more important contribution to environmental impacts than that from the chemical recovery process.

II. LCA applications for "hot spot" identification.

studies illustrate some of those assumptions, such as the choice of system boundaries and the weighting method. In some cases, the results of different studies on the same products appear contradictory, as illustrated by the case of paper bags [2–4]. The bags compared by Eurosac [3] were different from the ones in the first and third studies. Also, the studies by Franklin Associates [2] and Sevitz [4] use the same analytical unit (10,000 paper bags and the corresponding number of plastic bags), but were conducted in two different countries. The conclusions of the first study were based on inventory results only, while those of the third were based on impact results. This example shows that conclusions from LCA studies for product comparisons cannot be generalized. Several studies highlight the methodological challenges associated with this application of LCA [6–8].

Identification of "hot spots"

The identification of "hot spots" involves determining the contribution of each stage of the life cycle to the different impact categories. The main conclusions from some "hot spot" identification studies are presented in **Table II**. This table gives an overview of the potential for using LCA to evaluate energy, greenhouse gas emissions (GHG), and transportation issues in the pulp and paper industry. Other issues are also treated by the authors, but the focus in Table II is on energy issues. The studies show that LCA is a useful tool for investigating environmental strengths and weaknesses along the life cycle of a product. Some authors have noted the importance of combining LCA with other tools [14]. One important conclusion that can be drawn from several of the studies mentioned in Table II [9,10,17,18] is that ac-

REFERENCE	OBJECTIVES	MAIN CONCLUSIONS
Rafenberg and Mayer 1998 [19] France	Examination of newspapers of the LE MONDE group.	– The development of an improved version of LE MONDE depends less on technical than on management decisions. – LCA is useful for identifying and assessing the environmental impacts of a product and for improving management activities.
Vizcarra et al. 1999 [20] United States	LCI evaluation of the effects of substitution of wheat-straw chemical pulp for the softwood mechanical pulp component of telephone directory paper.	Straw pulp consumes more raw material and energy than mechanical pulp, mainly because its pulping chemicals cannot be recovered at this time.
Scheringer et al. 2000 [21] Switzerland	Comparison of the environmental performance of fluorescent whitening agents (FWAs) with peroxide bleaching of mechanical pulp.	– FWA production uses less energy. – LCA must be combined with risk assessment for better comparison of these options.
Dias et al. 2002 [13] Portugal	Comparison of elemental-chlorine-free (ECF) bleaching and total-chlorine-free (TCF) bleaching.	The current trend is to establish the best bleaching sequence for each wood species from an economic and environmental point of view.
Pineda-Henson et al. 2002 [22] USA	Analysis of process alternatives using LCA and analytical hierarchic process (AHP) analysis.	– The following process alternatives should be prioritized in this order to reduce environmental footprint: water recycling, alternative energy use, emissions control measures, and fiber recycling. – Combination of LCA and AHP provides a structured approach to environmental decision-making.
Lopes et al. 2003 [14] Portugal	Assessment of the replacement of heavy fuel oil (HFO) by natural gas and cogeneration in the manufacturing of paper.	– Substituting natural gas for HFO in the pulp and paper production process is a good environmental solution when combined with cogeneration. – LCA is an appropriate tool to evaluate the overall impact of process modifications.
Rehnström 2003 [15] Sweden	Comparison of a recovery boiler and black liquor gasification.	– Black liquor gasification is better for the environment than the classical recovery boiler. – To facilitate interpretation, a comparative LCA should be done of two paper mills equipped with the two recovery systems.
Das et al. 2004 [23] United States	Comparison of chemical, mechanical, and biopulping processes.	Biopulping leads to a significant reduction of environmental impact compared with the other processes.
Fu et al. 2005 [24] Canada	Assessment of the environmental benefits of enzyme bleaching compared with the classical ECF process.	– Results show that the introduction of enzyme bleaching into the ECF process improves performance in the majority of the impact categories. – The increase in GW and smog would be eliminated if the enzyme mediator were manufactured on site.
Munoz et al. 2005 [25] Spain	Comparison of advanced oxidation processes for dissolved organics removal.	– Energy is the main differentiator for the processes. – LCA was useful for comparing the different processes.

III. LCA applications for comparison of process technical options.

tivities upstream of paper production, in particular energy production, are often significant contributors to the life-cycle environmental impact.

Comparison of process technical options

LCA can be used to evaluate process variants. The comparison of variants with the initial process and with each other provides insight into the best opportunities for environmental improvement. Examples include comparisons of alternative bleaching processes, energy sources, and chemical recovery systems. **Table III** summarizes several studies of comparisons of process options using LCA. The usefulness of LCA for the evaluation of alternative energy sources has been demonstrated by various authors [14,18,25].

The examples presented in this table show that LCA alone is not sufficient to answer complex questions about process alternatives. Local impacts should be addressed using risk assessment because they are not well covered by LCA [21]. Furthermore, the combination of LCA with economic criteria and decision analysis methods has been discussed [13,22].

Comparison of waste management options

The large number of studies in **Table IV** demonstrates that waste management options have been widely studied using LCA. The conclusions of different studies can vary because of the methods used and the assumptions made (eg, fossil fuel energy replaced by incineration energy, virgin material replaced by recycled fibers). However, most studies illustrate the benefits of incineration and recycling over landfill disposal [15,19,24,27,32]. Recycling problems are complex to analyze using LCA because many assumptions have to be made about system boundaries, allocation procedures, and alternative usage of diverted material. For this reason, Ekvall and Finnveden [29–31] focused their efforts on the development of LCA methodologies specific to recy-

REFERENCE	OBJECTIVES	MAIN CONCLUSIONS
Karna et al. 1993 [26] Karna et al. 1994 [27] Finland	Comparison of scenarios for the life cycle of newsprint in the central European market.	Burning waste paper to generate electricity is better than recycling.
Grieg-Gran 1995 [28] United Kingdom	Summary of eight studies comparing incineration with heat recovery, recycling, and landfilling.	– Recycling has fewer benefits than energy recovery because of fossil fuel use. Energy sources are critical to this conclusion. – Social and economic issues related to paper recycling should be examined.
Ekvall 1996 [29] Ekvall & Finnveden 2000 [30] Ekvall 1999 [31] Sweden	Discussion of important methodological aspects related to wood fiber products and development of methodologies for the choice of system boundaries and allocation methods for recycling applications.	– Some important aspects influencing LCA results are: • Energy sources; • Assumptions regarding the alternative uses of biomass; • Inclusion/exclusion of indirect effects. – LCA should not be used alone for decision-making. – If LCA is used for decision-making, system boundaries should be expanded to include activities affected by the decision.
Grant et al. 2001 [32] Australia	Determination of the environmental benefits of recycling.	– Recycling provides substantial environmental benefits that come from avoided virgin material production and avoided landfill impacts. – LCA should be combined with assessment of technical, operational and economic reliability.
Pickin et al. 2002 [15] Australia	Investigation of various waste management options to reduce GHG emissions from paper.	Options other than landfill reduce GHG emissions. Waste-to-energy recovery is the most effective.
Dahlbo et al. 2005 [33]	Evaluation of impacts of different waste management options for the Helsinki region.	– LCI shows that the material and energy recovery options are superior to landfilling and that the energy recovery options are more favorable than recycling. – Several life-cycle impact analysis (LCIA) methods showed that co-combustion of newspaper performed better than material recycling or incineration if the recovered solid fuel can be used to replace coal.

IV. LCA applications for comparison of waste management options.

cling characteristics. Again, two crucial aspects are stressed: the importance of energy, and the necessity of using LCA with other tools to consider technical, economic, and social aspects of decision-making.

Evaluation of new products

Environmental aspects should be considered at each stage of the product life cycle, beginning with its design, to enable a better selection of materials and processes. Madu et al. [34] proposed a framework that includes the integral participation of consumers in environmentally conscious design and manufacturing. Using a case study involving paper recycling, they demonstrated that LCA is a good tool for assessing the environmental impact of each grade of paper and comparing alternatives. Currently, the pulp and paper industry is not using LCA extensively for the assessment of new products.

Strategic planning and evaluation

LCA can provide an organization or government with helpful information to support strategic choices as illustrated in **Table V**. For example, LCA can be used to choose suppliers based on environmental criteria [35], to develop environmental policies [36,40,41], or to respond to customer inquiries about environmental issues [37]. The example described by Zobel et al. [39] shows an opportunity to use LCA within an environmental management system (EMS). This specific case illustrates how LCA methodology can be used to identify the environmental aspects of pulp and paper mill operation.

CONCLUSIONS

LCA has been used since the 1990s for various pulp and paper applications, including comparison of products with the same function, identification of "hot spots," process analysis, comparison of process options, comparisons of end-of-life scenarios, evaluation of new products, and strategic evaluations. The main conclusions of this review can be summarized as follows:

- Comparison of competitive products is sensitive to subjective choices in LCA. LCA is more appropriately used as an engineering tool to identify environmental improvement opportunities and to compare process options.
- By examining the contribution of life-cycle stages to a product's overall environmental impact, it is possible to rationalize process improvement opportunities. In the studies considered, it has been demonstrated that energy production activities are an important contributor to overall environmental impact.
- When comparing process options using LCA, further value can be obtained by complementing the results with other system evaluation approaches such as techno-economic evaluation. The combination of environmental, technical, and economic criteria leads to complex comparisons, which can be rationalized using multicriteria decision-making methods. Use of such a combined approach is critical for some specific pulp and paper issues, such

REFERENCE	OBJECTIVES	MAIN CONCLUSIONS
SustainAbility 1995 [35] Europe	Application of LCA for supplier selection by pulp and paper companies.	– LCA is beginning to have commercial implications for industry. – Environmental pressures on suppliers are likely to increase across Europe, particularly if governments begin to include life-cycle management principles in their purchasing specifications.
Yaros 1996 [36] United States	Application of LCA for product development, capital expansion, elaboration of corporate energy policy, and audit program.	LCA is a useful tool that can be used to integrate the environmental dimension into business strategy for competitive advantage.
Côté 1996 [37] United States	Use of LCA to respond to the concerns of a pulp and paper company's customers about the environment.	LCA should not be used for "product bashing," but rather for improving environmental performance.
Bradley 1999 [38] Canada	Illustration of the significance that life-cycle thinking can have in the context of the paper chain.	– Using LCA enhances the stakeholders' knowledge about the environmental impacts of the paper chain and makes opportunities for improvement more obvious. – The importance of understanding the entire environmental picture before drawing conclusions is stressed.
Zobel et al. 2002 [39] Sweden	Proposal of a transparent and stringent methodology based on LCA for identification of environmental aspects and assessment within the EMS.	The use of LCA has two main advantages for this purpose: • Use of well-documented data; • Breaking the issues into tangible parts.
Ross & Evans 2002 [40] Ross et al. 2003 [41] Australia	Demonstration of how LCA can be used to determine the efficiency of policies for the reduction of a product's contribution to global environmental problems.	– In general, the most useful strategy is to recycle old packaging, except when direct measures to eliminate methane emissions are applied. – LCA can produce results relevant to policy-making by: • Identifying "hot spots"; • Elaborating the most desirable policy options; • Providing a quantitative basis for comparisons.
Dahlbo et al. 2005 [19]	Evaluation of impacts of different waste management targets for policy-making.	LCA is a method that is widely known, with strengths and weaknesses that are widely recognized. It can be used to provide information on the impacts of waste management targets for policy-making.

V. LCA applications for strategic planning and evaluation.

as recycling, which require a careful and well-described application of LCA methodology.

- The possibility of using LCA within environmental management systems has been identified. However, some major challenges for this application, such as definition of consistent system boundaries, remain to be addressed in a systematic fashion.
- Pulp and paper companies are beginning to see the potential of LCA for strategic planning. The most important application of LCA currently is for structuring supply chains.

The lack of good methods for assessing land use and for explicitly demonstrating the advantages of paper products in terms of carbon sequestration may be one reason why LCA is not more extensively used in the pulp and paper industry. **TJ**

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INSIGHTS FROM THE AUTHORS

Sustainability, in particular energy management and greenhouse gas (GHG) emissions, is increasingly critical to pulp and paper mills. Life-cycle assessment (LCA) produces a macro-scale evaluation of the environmental effects associated with the product chain, including global warming potential. However, to generate meaningful and trustworthy results, LCA must be carefully applied, often in conjunction with other methods. There is little information in the literature that addresses how LCA has been used in the pulp and paper industry, or which provides a critical analysis of the application methodology.

The survey and critical analysis were conducted to help guide the direction of an overall program, "Life Cycle Thinking in the Pulp and Paper Industry," being conducted as part of the Design Engineering Chair at École Polytechnique.

The most challenging aspect of this research was to counter LCA's reputation as a subjective method. It is critical to address this issue when applying LCA and communicating the approach and results, by an appropriate choice of applications, by full, rigorous, and transparent reporting of results, and by including sensitivity and uncertainty analyses.

Although there have been numerous LCA applications in the pulp and paper industry, and although LCA methodology has become well-defined with the ISO14040 guidelines, it was surprising to discover that pulp and paper companies have not adopted it more systematically. Potential value-added applications would include its adoption for demonstrating continuous environmental improvement and for mill strategic planning. It is hoped that mill personnel who read this article may be inspired to adopt LCA to improve the environmental decision-making processes in their company.

In the Design Chair at École Polytechnique, LCA is now being applied to develop comprehensive and transparent metrics that can be used in EMS and for strategic planning. These techniques are being explored using mill case studies. In the near future, a similar methodology will be used to examine process and product options for the forest biorefinery.

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