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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

SUMMARY OF THE LITERATURE ON THE TREATMENT OF PAPER AND PAPER PACKAGING PRODUCTS RECYCLING IN LIFE CYCLE ASSESSMENT

TECHNICAL BULLETIN NO. 985

MAY 2011

by
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Acknowledgments

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PRESIDENT'S NOTE

Questions related to the environmental aspects of recovering and recycling paper have led to a number of studies executed using the principles of life cycle assessment (LCA). While there are ISO standards that provide a consistent platform for LCA, a number of aspects that are decided by the researcher for case-specific reasons can render LCA studies more or less comparable. In particular, the treatment of paper and paperboard recycling in LCA requires selection of methodological options, none of which is inherently better or worse than the other, but which can significantly affect the LCA results. NCASI has undertaken this literature review to assist the forest products industry and its stakeholders in better understanding these methodological choices and their implications when applied to the treatment of paper recycling within LCA.

A review was undertaken of methodologies used in the literature for dealing with paper recycling life cycle assessment studies, to provide perspective as to their strengths and weaknesses in accurately reflecting the life cycle-related characteristics of the use of recycled fibre within the overall wood fibre system. The review also incorporated an examination of the factors (e.g., energy type) that have a significant effect on the LCA results. In all, 99 candidate studies were identified. Of the 99, 41 were retained for further analyses, having met several selection criteria.

The literature review enabled identification of the following seven overarching issues that either drive the results of paper recycling-related LCAs, or for which there is still too much uncertainty to fully understand their potential effect on LCA results. These included 1) impact of land use and alternative usage of the forest area; 2) type of energy used during virgin and recovered fibre processing; 3) type and amount of energy displaced when burning used paper at end-of-life; 4) accuracy of modelling toxicity-related impacts; 5) assumption regarding the degree of paper degradation in landfills and the approach used for modelling of biogenic carbon dioxide; 6) selected allocation procedure for recycling, in cases where virgin and recycled fibre are compared; and 7) recycled-to-virgin fibre substitution ratio.

Based on the literature reviewed in this study, the existing knowledge on LCA and paper recycling does not allow for general conclusions to be made regarding the overall environmental superiority of the use of recycled or virgin fibre for paper production. While many of the reviewed studies resulted in findings that suggest a lower LCA profile for recovery for recycling over landfilling as an end-of-life option for paper, the applicability of this finding is limited, given the extent to which it depends on assumptions regarding paper degradation in landfills and the methods used to account for biogenic carbon, and the relative weakness of current LCA toxicity-related impact assessment. The environmental analysis of recovery for recycling over burning for energy did not produce findings that can be generalized, primarily due to this question's sensitivity to the key issues mentioned above.

The inability to draw general environmental conclusions about paper recycling as explored through LCA is indicative of the degree to which methodological choices can affect the consistency of LCA results, the degree to which uncertainty exists within current LCA modelling for recycled fibre, and the sensitivity of LCA results to site-specific conditions inherent in a given recycled fibre system.

Ronald A. Yeske

May 2011

MOT DU PRÉSIDENT

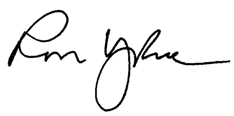
Les questions portant sur les aspects environnementaux de la récupération et du recyclage du papier ont fait l'objet d'un certain nombre d'études réalisées à l'aide des principes de l'analyse du cycle de vie (ACV). Même si les normes ISO existantes sur l'ACV offrent une plateforme uniforme de travail, certains aspects dans ces études ont été déterminés par les chercheurs pour des raisons bien spécifiques au cas étudié. Ces études sont donc difficilement comparables. Par exemple, pour traiter la question du recyclage du papier et du carton dans une ACV, il faut faire un choix parmi un certain nombre de méthodes. Aucune de ces méthodes n'est fondamentalement meilleure ou pire que les autres, mais le choix d'une méthode plutôt qu'une autre peut avoir un impact considérable sur les résultats d'une ACV. NCASI a donc entrepris une revue de la littérature pour aider l'industrie des produits forestiers et ses parties prenantes à mieux comprendre ces méthodes et leur impact lorsqu'elles sont utilisées pour étudier la question du recyclage du papier dans une ACV.

Dans sa revue de la littérature, NCASI a analysé les méthodes utilisées pour traiter la question du recyclage dans les études d'analyse de cycle de vie (ACV) afin de présenter un point de vue sur les avantages et les désavantages de ces méthodes à exprimer avec précision les caractéristiques d'utilisation de la fibre recyclée dans le cycle complet de la fibre ligneuse. La revue a également inclus une analyse des facteurs (p. ex. type de combustible) qui ont un impact considérable sur les résultats d'une ACV. Au total, NCASI a recensé quatre-vingt-dix-neuf (99) études admissibles et, parmi ces 99 études, NCASI en a retenues 41 pour une analyse plus poussée car elles avaient satisfait plusieurs critères de sélection.

Cette revue de la littérature a permis de mettre en lumière sept éléments déterminants qui, soit exercent une influence sur les résultats d'une ACV reliée au recyclage du papier, soit comportent trop d'incertitudes pour permettre de bien comprendre leur impact potentiel sur les résultats de l'ACV. Ces éléments sont les suivants : 1) l'impact de l'utilisation des terres et les autres utilisations des terres forestières; 2) le type de combustible utilisé durant le traitement de la fibre vierge et de la fibre récupérée; 3) le type et la quantité de combustible qu'on remplace lorsqu'on brûle des vieux papiers à la fin de leur vie utile; 4) la précision des étude de modélisation des impacts reliés à la toxicité; 5) les hypothèses sur le stade de décomposition du papier dans les sites d'enfouissement et l'approche utilisée pour modéliser le dioxyde de carbone biogénique; 6) la procédure de répartition choisie pour le recyclage lorsqu'on compare la fibre vierge et la fibre recyclée; et 7) le rapport de substitution entre la fibre recyclée et la fibre vierge.

Les résultats de cette revue de littérature ont montré que les connaissances actuelles sur l'ACV et sur le recyclage du papier ne permettent pas de tirer des conclusions générales au sujet de la supériorité environnementale globale de la fibre recyclée ou de la fibre vierge dans la fabrication du papier. Bien que bon nombre des études examinées ont fait ressortir des éléments qui semblent indiquer que la récupération présente un profil d'ACV plus faible et que le recyclage du papier constituerait donc une option de fin de vie supérieure à l'enfouissement, les possibilités d'application de cette conclusion sont limitées en raison des hypothèses sur lesquelles elle repose en matière de décomposition du papier dans les sites d'enfouissement, des méthodes utilisées pour comptabiliser le carbone biogénique et de la faiblesse relative des méthodes actuelles d'évaluation des impacts en matière de toxicité. L'analyse environnementale de la récupération du papier destiné au recyclage versus la récupération du papier destiné à la combustion pour produire de l'énergie n'a pas permis de tirer de conclusion générale en raison principalement de la sensibilité de cette question aux éléments déterminants mentionnés ci-dessus.

La revue de la littérature a montré qu'il n'était pas possible de tirer des conclusions environnementales générales sur le recyclage du papier dans le contexte d'une ACV, ce qui démontre bien à quel point le choix d'une méthode peut faire varier les résultats d'une ACV, à quel point il y a de l'incertitude dans les modèles actuels d'ACV qui s'appliquent au recyclage du papier et à quel point les résultats d'une ACV sont sensibles au conditions d'un site dans un système donné de fibres recyclées.



Ronald A. Yeske

Mai 2011

SUMMARY OF THE LITERATURE ON THE TREATMENT OF PAPER AND PAPER PACKAGING PRODUCTS RECYCLING IN LIFE CYCLE ASSESSMENT

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ABSTRACT

A review was undertaken of methodologies used in the literature for dealing with paper recycling in life cycle assessment (LCA) studies, to provide perspective as to their strengths and weaknesses in accurately reflecting the life cycle-related characteristics of the use of recycled fibre within the overall wood fibre system. The review also incorporated an examination of the factors (e.g., energy type) that have a significant effect on the LCA results. Of the 99 candidate studies, 41 were retained for further analyses, having met several selection criteria. A series of seven overarching issues were identified, which either drive the results of recycled fibre-related LCAs, or for which there is still too much uncertainty to fully understand their potential effect on LCA results. These included 1) impact of land use and alternative usage of the forest area; 2) type of energy used during virgin and recovered fibre processing; 3) type and amount of energy displaced when burning used paper at end-of-life; 4) accuracy of modelling toxicity-related impacts; 5) assumption regarding the degree of paper degradation in landfills and the approach used for modelling of biogenic carbon dioxide; 6) selected allocation procedure for recycling, in cases where virgin and recycled fibre are compared; and 7) recycled-to-virgin fibre substitution ratio. Based on the literature reviewed in this study, the existing knowledge on LCA and paper recycling does not allow for general conclusions to be made regarding the overall environmental superiority of the use of recycled or virgin fibre for paper production.

KEYWORDS

life cycle assessment, paper and paper packaging products, recycling

RELATED NCASI PUBLICATIONS

Special Report No. 09-04 (April 2009). *Review of LCA Allocation Procedures for Open-Loop Recycling Used in the Pulp and Paper Industry*.

RÉSUMÉ DE LA REVUE DE LITTÉRATURE SUR LES MÉTHODES UTILISÉES POUR TRAITER LA QUESTION DU RECYCLAGE DES PRODUITS DU PAPIER ET D'EMBALLAGE DE PAPIER DANS UNE ANALYSE DE CYCLE DE VIE

BULLETIN TECHNIQUE NO. 985
MAI 2011

RÉSUMÉ

NCASI a analysé les méthodes utilisées pour traiter la question du recyclage dans les études d'analyse de cycle de vie (ACV) afin de présenter un point de vue sur les avantages et les désavantages de ces méthodes à exprimer avec précision les caractéristiques d'utilisation de la fibre recyclée dans cycle complet de la fibre ligneuse. La revue a également inclus une analyse des facteurs (p. ex. type de combustible) qui ont un impact considérable sur les résultats d'une ACV. Au total, NCASI a recensé quatre-vingt-dix-neuf (99) études admissibles et, parmi ces 99 études, NCASI en a retenues 41 pour une analyse plus poussée car elles avaient satisfait plusieurs critères de sélection. Cette revue de la littérature a permis de mettre en lumière sept éléments déterminants qui, soit exercent une influence sur les résultats d'une ACV reliée au recyclage du papier, soit comportent trop d'incertitudes pour permettre de bien comprendre leur impact potentiel sur les résultats de l'ACV. Ces éléments sont les suivants : 1) l'impact de l'utilisation des terres et les autres utilisations des terres forestières; 2) le type de combustible utilisé durant le traitement de la fibre vierge et de la fibre récupérée; 3) le type et la quantité de combustible qu'on remplace lorsqu'on brûle des vieux papiers à la fin de leur vie utile; 4) la précision dans les études de modélisation des impacts reliés à la toxicité; 5) les hypothèses sur le stade de décomposition du papier dans les sites d'enfouissement et l'approche utilisée pour modéliser le dioxyde de carbone biogénique; 6) la procédure de répartition choisie pour le recyclage lorsqu'on compare la fibre vierge et la fibre recyclée; et 7) le rapport de substitution entre la fibre recyclée et la fibre vierge. Les résultats de cette revue de littérature ont montré que les connaissances actuelles sur l'ACV et sur le recyclage du papier ne permettent pas de tirer des conclusions générales au sujet de la supériorité environnementale globale de la fibre recyclée ou de la fibre vierge dans la fabrication du papier.

MOTS CLÉS

analyse de cycle de vie, produits du papier et d'emballage de papier, recyclage

PUBLICATIONS DE NCASI RELIÉES

Rapport spécial n° 09-04 (avril 2009). *Revue des règles d'allocation dans les ACV appliquées au recyclage en circuit ouvert dans l'industrie des pâtes et papiers*.

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EXECUTIVE SUMMARY

Background and Objectives

The Forest Products Association of Canada (FPAC) commissioned the National Council for Air and Stream Improvement (NCASI) to perform a review of the literature on the treatment of paper recycling in life cycle assessment (LCA) studies. Given the interconnected nature of the global recycled and virgin fibre system and the extent to which external factors such as government policy and fibre supply economics can affect the degree and manner in which recovered fibre is used, there is no universally accepted approach for addressing recycled fibre in LCA studies. That said, there are methodologies applied that do a more (or less) effective job of accurately reflecting the fibre system in relation to environmental releases or impacts. The purpose of this report is to identify these currently used methodologies and provide perspective as to their strengths and weaknesses in assessing the life cycle-related characteristics of the use of recycled fibre within the overall wood fibre system.

More specifically, the objectives of this study were to:

1. Perform an inventory of LCA studies dealing with paper recycling including
    a. Studies with an emphasis on improving the methods related to recycling in LCA and more specifically recycling of paper;
    b. Studies that synthesize the existing literature on LCA and paper recycling;
    c. Studies using a societal perspective (e.g., for assisting policy-making regarding paper recycling); and
    d. Studies using a company perspective (i.e., for which the objective is to support internal environmental improvements).
2. For each methodological study and previously published literature review, summarize a) the proposals for improving the methods related to paper recycling in LCA and b) key issues that were identified for paper recycling LCA applications;
3. For each case study, summarize a) the methods employed, b) the treatment of key issues, and c) the results and findings, and comment on the implications of treatment of the key issues to the results; and
4. Identify the overarching aspects that have a significant effect on results of LCAs related to paper recycling and identify knowledge gaps.

Methodology

This literature review was undertaken using the following steps. First, an inventory of existing studies on paper recycling was prepared and studies were either retained for further analysis or dismissed based on a set of predefined criteria (availability of background information, consistency with the ISO standards on LCA, date of publication and specificity to "paper"). The retained studies were summarized. Methodological documents and existing reviews of the literature were used to develop a list of potential key issues for the application of LCA to paper recycling applications. Then, case studies were reviewed in the context of their treatment of these key issues. Finally, overarching aspects and knowledge gaps were identified.

Results

Inventory and Classification of Studies

In all, 99 candidate studies were identified. A large proportion of the studies on paper recycling included case studies using a societal perspective. Fewer of the candidate studies had been performed on a case-specific company context. Within the candidate studies, end-of-life options for paper (i.e., landfill, burning for energy recovery or recovery for recycling in new paper products) are compared much more frequently than virgin and recycled paper. Of the 99 documents, only 41 were retained for further analyses. The main reasons for the exclusion of the other 58 documents were 1) the study did not align with the ISO standard, 2) the document was not available in English or French, and/or 3) the document was essentially redundant with other documents included in the review. The relative classification of the 41 retained studies is similar to the classification of the entire set of candidate studies, though the retained studies more frequently address recycling in the context of the life cycle attributes of paper products as opposed to the examination of alternatives for managing used paper.

Identification of Potential Key Issues

Based on the methodological papers and previous literature reviews, 15 issues (11 system boundary-related, 2 impact assessment-related and 2 data-related) were identified as being of potential significance to paper recycling LCA results. These are presented below.

System Boundary Issues

1. **Forest management activities:** In LCA, the system boundaries should be set so as to begin with all activities required for the acquisition of raw materials and end with the final disposal of manufacturing wastes and discarded product. For wood products, the primary raw material is wood. How the boundary is set around the forest management activities can have a quantitative effect on LCA study results.
2. **Alternative use of the forest land and of the wood:** All other things being equal, increased use of recovered fibre is likely to result in a reduced demand for pulpwood, which in turn could result in a decreased volume of wood required from forest land. Several different assumptions, which can be highly influential on the conclusions of an LCA on paper recycling, can be made regarding the alternative use of the forest and of the wood.
3. **Treatment of sawmill co-products:** Wood chips, which are the main raw material for producing virgin pulp, are often produced as a co-product of sawmilling activities (i.e., wood that is unusable as lumber is sometimes chipped and sold for pulp production). The manner in which the environmental loads attributable to sawmilling activities are allocated between lumber (the main product of sawmilling activities) and other co-products such as chips can have a quantitative effect on the study results.
4. **Energy use during virgin and recovered fibre processing:** One of the most important issues in evaluating paper recycling is the energy used in manufacturing. While the energy needs for virgin fibre processing can be fulfilled, at least in part, by self-generated bio-based energy (wood wastes, pulping liquor), recycled fibre processing generally depends on fossil fuels.
5. **Energy exports at virgin fibre processing:** Chemical pulping can produce an excess of energy that can be exported to the public power grid. This needs to be accounted for accurately, in cases where energy export is undertaken. It should be noted that the type of energy (i.e., fuel type and whether it is as power or heat) displaced by these exports can have a significant effect on the LCA results.
6. **Handling of rejects from recovered fibre processing:** Although quantitative environmental information on management of deinking wastes and on their level of contaminants is not always

available, these wastes can have a significant effect on LCA results, partly due to the large quantities of waste sometimes involved.

7. **Landfill emissions:** Paper partly decomposes when put into a landfill, resulting in emissions to air and water. Limited knowledge on landfill processes and the large variation in conditions between and within landfills make the modelling of landfill emissions very uncertain. In addition, emissions of greenhouse gases from landfills are affected by a variety of other factors.
8. **Energy exports related to burning waste paper:** Energy can be recovered when paper is burned at its end-of-life. Hence, waste paper burning fulfills two functions (waste management and energy production) and there is an allocation problem if the energy produced is used in another product system. Several alternative methods can be used to resolve this allocation problem, which can lead to significant quantitative effects on the results.
9. **Allocation strategy for recycling:** In open-loop recycling, recovered fibre is recovered from one product system and then recycled into another product system (e.g., recycling of office paper into tissue). Many allocation strategies can be found in the literature to deal with this situation. The choice among these strategies can lead to critical differences in results, when the objective of an LCA is to compare virgin and recycled raw material or to compare different waste management strategies for paper.
10. **Substitution effects:** There is a connection between the recovery *rate* and the recovered fibre *content* of paper products; however, this connection is not always direct. Indeed, conclusions from an LCA investigating one cannot be used directly to make conclusions about the other. A specific paper grade may be highly recovered, for example due to recovery efficiency or desired recovered fibre characteristics (e.g., strength or brightness), but may be reused largely in production of other paper grades. For instance, used office paper in North America is highly recovered, but office paper itself has low recovered fibre content because the recovered office paper is recycled into other paper grades (e.g., paperboard, tissue, and other printing and writing papers). Recovery rate and recovered fibre content have been studied separately and in connection. Studying an increase in only one of these without examining the effects in the other can lead to unrealistic LCA results, given the complex connections between the two. For example, such an LCA could produce results that are reliant on availability of more recovered fibre than is actually available in the marketplace, or more recycling processing capacity than currently exists. In cases where the interconnection of the two *is* considered, another factor that can be important to the results is the assumption that is made regarding the type of virgin pulp production that is avoided due to an increase in the recovery rate.
11. **Biogenic carbon cycle:** The importance of comprehensive treatment of biogenic carbon is generally not recognized by currently available methodological papers that deal with paper recycling. However, the connections between climate change and the product value chain are perhaps more complex in the forest industry than in any other industry. Forests remove carbon dioxide from the atmosphere and store the carbon not only in trees, but also below ground in soil and root systems. Ultimately, the carbon in harvested wood is then either stored in forest products and landfills for a certain period or reemitted to the atmosphere. It can be returned to the atmosphere as carbon dioxide or methane, each of which has different impacts on the atmosphere. How biogenic carbon is accounted for in LCA studies can potentially have a significant quantitative effect on the LCA's results.

<u>**Data Issues**</u>

12. **Data gaps and quality:** While undertaking an LCA, many data gaps can arise that are not readily filled. Also, available data can be of various levels of quality. Data gaps and data quality can have a significant effect on the results of an LCA; therefore, providing commentary on the quality and sufficiency of data are a vital addition to contextualizing an LCA's results.
13. **Average and marginal data for electricity production:** Electricity production is often a significant contributing factor to the environmental impacts reviewed in LCAs of paper products.

The choice between using data representing “average” versus “marginal” electricity consumption conditions can have significant impacts on the results, when the difference in electricity consumption is an important aspect within the scenarios investigated.

Impact Assessment Issues

14. **Land use impacts:** Several methods have been proposed and used to estimate the environmental impacts of forestry. Forestry impacts are multidimensional and not as readily quantified, and are thus difficult to describe accurately in LCA terminology. At this time, there is no consensus on how land use impacts, such as effects on biodiversity, should be included in LCA.
15. **Toxicity-related impacts:** For a comparison of waste management alternatives to be based on a comprehensive set of environmental concerns, as required in the ISO standard, human and ecosystem toxicity indicators should be included in an LCA. In practice, however, these indicators are rarely included in LCA studies because different methods (which are still largely under development) usually fail to arrive at the same toxicity characterization score for a given substance. The reason for this is that human and ecosystem toxicity methods are based on multiple parameters such as the location of the emission, the location of the receptor, and/or the time period during which the potential contribution to the impact is taken into account. In practice, LCA studies are generally not sufficiently detailed to enable consideration of many of these variables.

Treatment of Key Issues in Case Studies

The review of case studies revealed that the 15 key issues presented above are not always systematically or consistently dealt with. However, it is possible to synthesize seven overarching issues that either drive the results of paper recycling LCAs, or for which there is still too much uncertainty to fully understand their potential effect on LCA results.

- Impact of land use and alternative usage of the forest area
- The type of energy (i.e., fuel type and whether it is as power or heat) used during virgin and recovered fibre processing
- Type and amount of energy displaced when burning used paper at end-of-life
- Accuracy of modelling toxicity-related impacts
- Assumption regarding the degree of paper degradation in landfills and the approach used for modelling of biogenic carbon dioxide;
- The selected allocation procedure for recycling, in cases where virgin and recycled paper are compared
- Recycled-to-virgin fibre substitution ratio

Conclusions

The main objective of this study was to identify and analyze the literature that deals with paper recycling in LCA. More specifically, the following types of studies were included: studies with an emphasis on improving the methods related to paper recycling in LCA; studies that synthesize the existing literature on LCA and paper recycling; case studies comparing various end-of-life options for paper (landfill, burning for energy recovery and recovery for recycling); and case studies comparing the use of virgin and recycled fibre for paper production.

Based on this literature, it is concluded that the existing knowledge on LCA and paper recycling does not allow for general conclusions to be made regarding the overall environmental superiority of using recycled or virgin fibre for paper production.

That said, many of the reviewed studies resulted in findings that suggest a lower LCA profile for paper recovery for recycling over landfilling as a used paper end-of-life option. The applicability of this finding, however, is limited, given the extent to which it depends on assumptions regarding paper degradation in landfills and the methods used to account for biogenic carbon. Also, the weakness of current toxicity-related impact assessment modelling approaches could be a limitation to this finding.

The environmental analysis of recovery for recycling and burning with energy recovery as end-of-life options for paper did not produce findings that can be generalized, primarily due to this question's sensitivity to the key issues mentioned above.

There is opportunity to improve the consistency and transparency of the treatment of paper recycling within LCA, particularly by using it in conjunction with system-oriented tools such as material-flow analysis, to design an optimal fibre flow that accounts for process specificities and fibre degradation. It would also be helpful to develop more case-specific comparisons of recycling and incineration that account for such an optimal fibre flow, and to develop enhanced impact assessment methods for toxicity and land use impacts.

CONTENTS

TABLES

FIGURES

SUMMARY OF THE LITERATURE ON THE TREATMENT OF PAPER AND PAPER PACKAGING PRODUCTS RECYCLING IN LIFE CYCLE ASSESSMENT

1.0 INTRODUCTION

1.1 Context

The present study has been prepared by the National Council for Air and Stream Improvement (NCASI) for the Forest Products Association of Canada (FPAC). The study was commissioned to summarize the approaches currently being used when considering recycled fibre in the context of life cycle assessment (LCA). Given the interconnected nature of the global recycled and virgin fibre system and the extent to which external factors such as government policy and fibre supply economics can affect the degree and manner in which recovered fibre is used, there is no universally accepted approach for mathematically addressing recycled fibre in LCA studies. That said, there are methodologies applied that do a more (or less) effective job of accurately reflecting the fibre system in relation to environmental releases or impacts. The purpose of this report is to synthesize these currently used methodologies and provide perspective as to their strengths and weaknesses in accurately reflecting the life cycle-related characteristics of the use of recycled fibre within the overall wood fibre system.

1.2 Objective and Scope

The objectives of this study are:

1. Perform an inventory of LCA studies dealing with paper recycling including
    a. Studies with an emphasis on improving the methods related to recycling in LCA and more specifically recycling of paper;
    b. Studies that synthesize the existing literature on LCA and paper recycling;
    c. Studies using a societal perspective (e.g., for assisting policy-making regarding paper recycling); and
    d. Studies using a company perspective (i.e., for which the objective is to support internal environmental improvements).
2. For each methodological study and previously published literature review, summarize a) the proposals for improving the methods related to paper recycling in LCA and b) key issues that were identified for paper recycling LCA applications;
3. For each case study, summarize a) the methods employed, b) the treatment of key issues, and c) the results and findings, and comment on the implications of treatment of the key issues to the results; and
4. Identify the overarching aspects that have a significant effect on results of LCAs related to paper recycling and identify knowledge gaps.

The literature review is framed using an approach previously used in an LCA literature review performed for the European Environment Agency (EEA). This prior study systematically identified and assessed the system parameters and boundary assumptions found to be most influential to the conclusions obtained in the LCA studies. The EEA literature review was published in several different formats between 2005 and 2007 (EEA 2006; Villanueva and Wenzel 2007; Wenzel and Villanueva 2006) and included studies (mostly European) published between 1991 and 2005. It emphasized the analysis of waste management options for paper, primarily from a societal perspective. The literature review presented here is an update and extension of the previous EEA study and it includes papers published after 2005. It also takes a broader perspective on recycling rather than focusing only on waste management.

The intent of this study is to present the individual study conclusions and aggregate findings, but not to make assertions as to their accuracy.

2.0 BACKGROUND INFORMATION

2.1 Definitions

Allocation

Allocation is the *"partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems"* (ISO 2006b, 4).

Co-Product

A co-product is *"any of two or more products coming from the same unit process or product system"* (ISO 2006b, 3).

Foreground and Background Systems (and Processes)

A product system can be divided into the foreground and background subsystems. The foreground system is *"the collection of unit processes on which measures may be taken concerning their selection or mode operation as a result of decisions based on the study"* while the background system *"consists of all other modeled processes influenced by measures taken in the foreground system"* (Tillman 2000, 118). Most often, primary data are collected for foreground processes, and secondary data for background processes (Guinée et al. 2002).

Cradle-to-Grave and Cradle-to-Gate

A cradle-to-grave approach uses an *"LCA model which includes the whole product life cycle, i.e. all steps from raw material extraction to waste disposal"*. In contrast, a cradle-to-gate approach uses an *"LCA model which includes upstream part of the product life cycle, i.e. all steps from raw material extraction to product at the factory gate"* (Baumann and Tillman 2004, 530).

Characterization

Characterization is a step in life cycle impact assessment (LCIA) where the category indicator (quantifiable representation of an impact category) results are calculated (ISO 2006b).

Function

ISO does not provide a formal definition for function. However, it states that *"the scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied"* (ISO 2006b, 8).

Functional Unit

The functional unit is the *"quantified performance of a product system for use as a reference unit"* (ISO 2006b, 4).

Life Cycle Impact Assessment (LCIA)

LCIA is the "*phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product"* (ISO 2006b, 2). Several methods are available for this purpose.

- **CML Method:** The CML 2 baseline method (Guinée et al. 2002) uses a problem-oriented (midpoint) approach. Impact categories are classified in 1) obligatory impact categories (used in most LCAs); 2) additional impact categories (where operational indicators exist, but are not often included in LCA studies); and 3) a listing of other impact categories (where no operational indicators are available and therefore impossible to include quantitatively in LCA). The method includes factors for characterization and normalization. More information can be found on the website (http://www.leidenuniv.nl/interfac/cml/ssp/lca2/index.html).

- **DAIA Method:** DAIA stands for "Decision Analysis as a Tool for Impact Assessment". This method uses decision analysis concepts to rank different options as well as the environmental stressors in a comparative LCA, based on to their potential of giving rise to adverse environmental effects. Source: http://www.ymparisto.fi/default.asp?contentid=84940&lan=EN.
- **Eco-Indicator 95:** The Eco-indicator 95 method was developed under the Dutch NOH programme by PRé consultants in a joint project with Philips Consumer Electronics, NedCar (Volvo/Mitshubishi), Océ Copiers, Schuurink, CML Leiden, TU-Delft, IVAM-ER (Amsterdam) and CE Delft. It includes factors for characterization, normalization and weighting. Source: http://www.pre.nl/content/reports.
- **Eco-Indicator 99:** The Eco-indicator 99 method comes in three versions, the Egalitarian, Individualist and the Hierarchist (default) versions. Normalization and weighting are performed at the damage category level. Three damage categories are used: 1) human health (unit: DALY = Disability Adjusted Life Years; this means different disabilities caused by diseases are weighted), 2) ecosystem quality (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species), and 3) resources (unit: MJ surplus energy= Additional energy requirement to compensate lower future ore grade). Source: http://www.pre.nl/content/reports.
- **EDIP 1997/2000:** EDIP is a European midpoint method that includes characterization, normalization, and weighting (Wenzel and Hauschild 1997; Wenzel et al. 1997).
- **EPS system:** EPS stands for Environmental Priority Strategies in product design. The objective of the EPS system is to serve as a tool for a company's internal product development process. It has rules for accomplishing the various tasks of impact assessment including the selection of impact categories, assignment of emissions to impact categories, characterization and weighting. More information can be found at http://eps.esa.chalmers.se/Default.htm.
- **LUCAS:** LUCAS is a Canadian impact assessment methodology that uses a set of site-dependent characterization factors for the 15 Canadian terrestrial ecozones (Toffoletto et al. 2007).
- **TRACI:** TRACI stands for the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. It was developed by the U.S. Environmental Protection Agency. It includes characterization and normalization factors proposed by (Bare et al. 2003). More information is at http://www.epa.gov/ORD/NRMRL/std/sab/traci/.

Material Flow Analysis (MFA)

MFA is a method of analyzing the flows of a material in a well-defined system that is used to produce better understanding of the flow of materials through an industry and connected ecosystems.

Midpoint and Endpoint Approaches

Midpoint, or problem-oriented, approaches for LCIA use a "*a point in the cause-effect chain (environmental mechanism) of a particular impact category, prior to the endpoint, at which characterization factors can be calculated to reflect the relative importance of an emission or extraction in a Life Cycle Inventory (LCI) (e.g., global warming potentials defined in terms of radiative forcing and atmospheric half-life differences)*" (Bare et al. 2000, 319). In endpoint, or damage-oriented approaches, category indicators are selected to characterize the impacts to four different areas including human health, natural resources, natural environment, and man-made environment, which are referred to as areas of protection (Guinée et al. 2002).

Normalization
Normalization consists of *"calculating the magnitude of category indicator results relative to reference information"* in order to *"understand better the relative magnitude for each indicator result of the product system under study"* (ISO 2006b, 20).

Open-Loop Recycling
For the purposes of this study, open-loop recycling is recycling of material generated in one product system into a different product system.

Primary and Secondary Data
Primary data are data specific to the processes studied, while **secondary** data are from databases, literature, or estimations.

Product System
The product system is the *"collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product"* (ISO 2006b).

Unit Process
A unit process is the *"smallest element considered in the life cycle inventory analysis for which input and output data are quantified*"(ISO 2006b).

Waste Hierarchy
In many countries, policies for waste management are characterized by the following hierarchy of options: 1) waste minimization, 2) reuse, 3) recycling, 4) energy recovery, and 5) landfill (Byström and Lönnstedt 1997; EEA 2006; Finnveden et al. 2005; Schmidt et al. 2007).

Weighting
Weighting is defined as *"the process of converting indicator results of different impact categories by using numerical factors based on value-choices"* (ISO 2006b, 22). The ISO 14044 also specifies that *"it may include aggregation of the weighted indicator results"*.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*", the life cycle being "*consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal*" (ISO 2006a, 2).

LCA principles and methodology are framed by a set of standards and technical reports (TR) and technical specifications (TS) from the International Organization for Standardization (ISO). ISO describes LCA methodology in four phases (as illustrated in Figure 2.1):

1. **Goal and scope definition** in which the aim of the study, the product system under study as well as its function and functional unit, the intended audience and the methodological details on how the study will be performed are defined;
2. **Life cycle inventory analysis (LCI)** which is the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 2006a, 2);

3. **Life cycle impact assessment (LCIA)** which is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 2006a, 2); and
4. **Life cycle interpretation** which is the phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 2006a, 2).

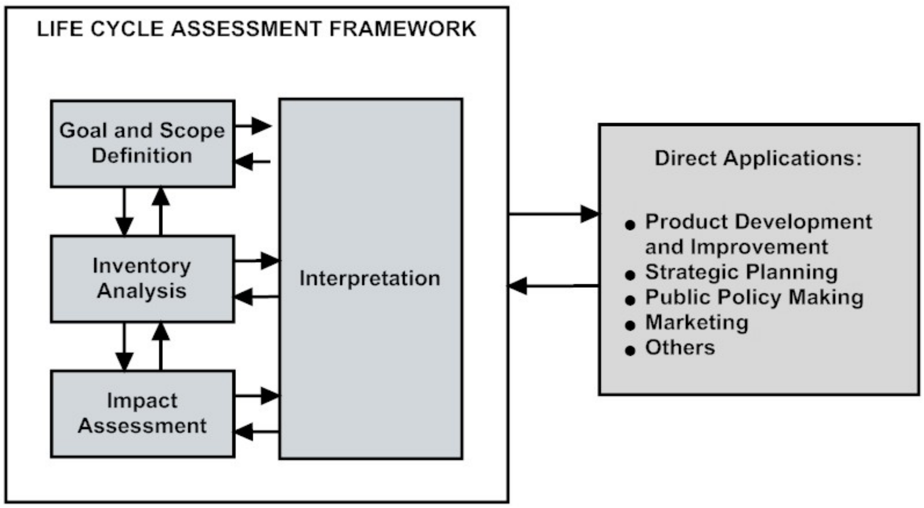

Figure 2.1 Life Cycle Assessment Phases (ISO 2006a)

ISO provides guidelines for applying LCA in two standards and three technical reports or technical specifications. These are presented in Table 2.1.

Table 2.1 ISO Standards and Technical Reports for LCA

Document Number	Title	Reference
ISO 14040	Environmental management - Life cycle assessment - Principles and framework	(ISO 2006a)
ISO 14044	Environmental management - Life cycle assessment - Requirements and guidelines	(ISO 2006b)
ISO/TR 14047	Environmental management - Life cycle impact assessment - Examples of application of ISO 14042[a]	(ISO 2003)
ISO/TS 14048	Environmental management - Life cycle assessment - Data documentation format	(ISO 2002)
ISO/TR 14049	Environmental management - Life cycle assessment - Examples of application of ISO 14041[2] to goal and scope definition and inventory analysis	(ISO 2000)

[a] The ISO series was revised in 2006. The current ISO 14044 standard replaces the ISO 14041/42/43 standards from the first edition.

2.3 What Is an Allocation Problem?

During the LCI phase, the mass, energy, and pollutants that cross the system boundary are quantified. A difficulty arises in this quantification when the system boundary includes multifunctional unit processes or if the entire product system is multifunctional in nature. An example of the former could be the production of kraft pulp where pulp is used within the boundary to produce paper but the turpentine is sold to be used in another product system. Systems involving open-loop recycling [e.g., recycling of discarded printing and writing (P&W) paper in tissue products] are an example of product systems that are multifunctional in nature. In this example, the used paper produced as a result of the production of P&W paper provides a function (raw material) to the tissue production. In the two cases described above, the challenge is to decide how the quantified mass, energy, and pollutant flows should be divided (i.e., allocated) between the different systems. There is a wide variety of methods to perform allocation. At present, there is no consensus amongst LCA practitioners regarding which one should be used for what type of application. The method selected, however, may have a substantial influence on the final quantitative results of an LCA.

2.4 The ISO 14044 Requirements for Recycling

To put the results of the literature review in context, it is useful first to present the main ISO 14044 requirements for LCA studies involving recycling. The general ISO 14044 requirements for allocation follow.

- *“The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure.*

- *“The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.”*

- *“Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach”* (ISO 2006b, 14).

The ISO 14044 procedure for co-product allocation is, in order of preference: 1) avoid allocation wherever possible by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or expanding the product system to include the additional functions related to the co-products; 2) where allocation cannot be avoided, partition the inputs and outputs of the system to its different products or functions in a way that reflects the underlying physical relationships between them (in a way that reflects how they are changed by quantitative changes in the products or functions delivered by the system); and 3) where physical relationship alone cannot be established or used as the basis for allocation, allocate the inputs and outputs between the products and functions in a way that reflects other relationships between them (e.g., in proportion to the economic value of the co-products).

The ISO 14044 standard specifies that the previous allocation procedure is also applicable to reuse and recycling but it provides additional elaboration regarding open-loop recycling.

- *"Reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system."*

- *"Reuse and recycling may change the inherent properties of materials in subsequent use."*

- *"Specific care should be taken when defining system boundary with regard to recovery processes"* (ISO 2006b, 15).

The standard states that a closed-loop approach can be taken if no changes occur in the inherent properties of the recycled material. Otherwise, the shared unit processes should use the following as the basis for allocation, if feasible, in order of preference: physical properties (e.g., mass); economic value (e.g., market value of the scrap material or recycled material in relation to market value of primary material); or the number of subsequent uses of the recycled material [as described in the ISO 14049 technical report (ISO 2000)].

2.5 The Paper Cycle

A simplified example of the paper life cycle is illustrated in Figure 2.2. It starts with the removal of carbon dioxide from the atmosphere during the growing of trees. In cases where the paper would be produced from a tree plantation, however, it would start with the production of seedlings. Then, the tree is harvested, debarked, and chipped for pulp production. There are two main types of virgin fibre pulping processes: mechanical pulping and chemical pulping. Pulp can also be made out of recovered fibre. Fibres can be bleached to achieve the desired brightness. Bleached and unbleached fibres are suspended in water and poured on a fast-moving mesh to form paper sheets that are pressed and dried. They are then transformed into the final product through various conversion activities such as sheet cutting, printing, box production, etc. Uses for paper are multiple. Once it has been used, it is usually recovered (e.g., for recycling) or discarded. The discarded fraction can be landfilled, composted, or burned (with or without energy recovery). In modern landfills, a portion of the paper is slowly decomposed, producing leachate and landfill gas (carbon dioxide and methane). Methane from landfills can be captured and burned.

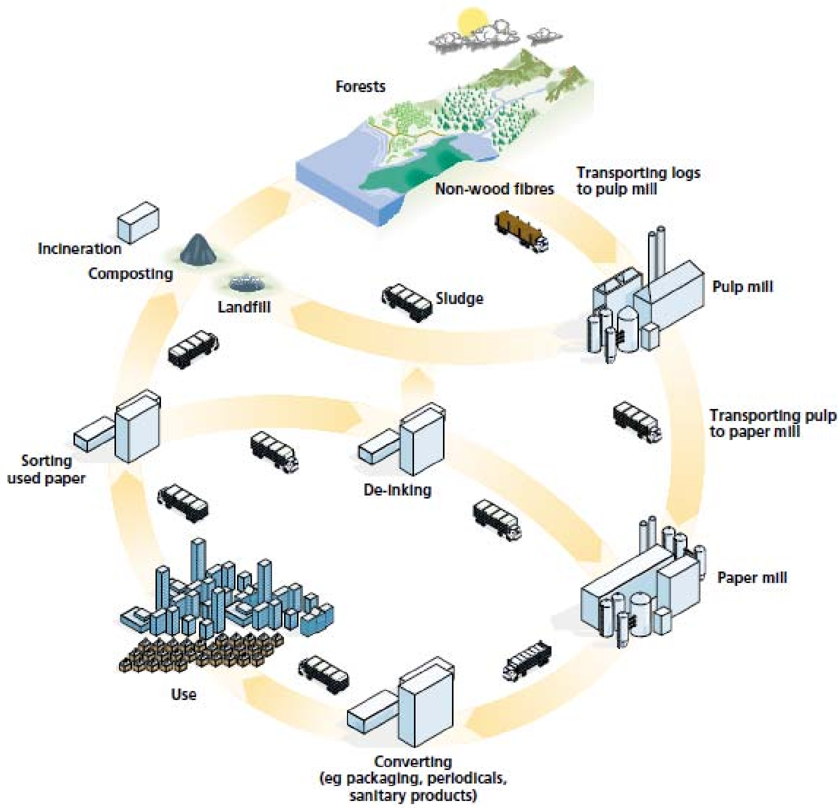

Figure 2.2 Simplified Life Cycle of a Paper Product
(International Institute for Environment and Development 1996)
<u>Note</u>: For simplicity's sake, no release to air, water or soil, or inputs other than water are shown in the figure.

3.0 METHODOLOGY

This literature review was undertaken using the following steps:

1. Inventory of existing LCA studies
    a. Identification of relevant studies
    b. Classification of the studies
    c. Selection of studies based on a set of criteria
2. Summary of retained methodological studies and previously published literature reviews
3. Summary of case studies and detailed review in the context of their treatment of the key issues
4. Identification of the overarching aspects and knowledge gaps

These steps are discussed in greater detail in the next sections.

3.1 Inventory of Existing LCA Studies

3.1.1 Identification of Relevant Studies

The first step of this study was a thorough search of the peer-reviewed and gray literature for LCA studies related to recovered paper recycling. The search was limited to publicly available studies published in English or in French. The previous literature review by the EEA (EEA 2006; Villanueva and Wenzel 2007; Wenzel and Villanueva 2006) was used as an initial source for references, and then the search was extended to literature search engines and by contacting worldwide organizations or individuals with expertise in paper and/or LCA, including a committee comprised of FPAC and NCASI member companies.

3.1.2 Classification of Studies

Studies on waste paper recycling can be classified according to their type (i.e., methodological discussion of the appropriateness of LCA as a tool for assessment of paper systems, literature review, or case study that uses LCA as a tool for assessment of paper systems), their perspective (i.e., societal[1] or company-specific), their objectives in terms of paper recycling (i.e., comparing end-of-life option for used paper or comparing virgin and recycled paper), and the function of the system investigated (i.e., management of used paper product or production of a paper product for a certain usage). This is illustrated in Table 3.1.

The original study by the EEA focused on analyzing LCA studies intended to support the selection of a strategy for the management of used paper using a societal perspective. This literature review is broader in that it includes all categories presented in Table 3.1.

Table 3.1 Classification of Studies Reviewed

Type of document	Perspective	Objective	Function of the system investigated
1. Methodological papers	A. Societal	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage
	B. Company	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage
2. Literature reviews	A. Societal	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage
	B. Company	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage

[1] In contrast to "company-specific" studies, studies employing a societal perspective address the recycling question at a country or region level.

Type of document	Perspective	Objective	Function of the system investigated
3. Case studies	A. Societal	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage
	B. Company	a) comparison of end-of-life options	i) management of used paper product
			ii) production of a paper product for a certain usage
		b) comparison of virgin and recycled paper	ii) production of a paper product for a certain usage

3.1.3 Selection of Studies Based on a Set of Criteria

From an initial list of nearly 100 references, a subset of the identified studies was retained as having met the criteria for further analysis. Studies were selected based on four criteria (EEA 2006; Villanueva and Wenzel 2007, Wenzel and Villanueva 2006):

1. availability of background information;
2. consistency with the ISO standards on LCA (ISO 2006a, 2006b);
3. date of publication; and
4. specificity to “paper”.

While the original EEA literature review also eliminated any studies that did not include a comparison between recycling and alternative disposal scenarios because these studies would not have been helpful in illuminating the benefits and drawbacks of the different options, no study has been eliminated on this basis for the current project. The objective of this current study is to develop a general picture of the literature related to the treatment of paper recycling within LCA, rather than to draw any conclusion regarding the environmental superiority or inferiority of recycling.

3.1.3.1 Criterion 1: Availability of Background Information

The methods employed and the assumptions made within the studies to be reviewed need to be transparent for the studies to be retained for further analysis. This is necessary to better contextualize the results obtained. For this reason the preferred study formats are as follows:

1. full LCA report;
2. ISO-conforming third-party report; or
3. other detailed summary and scientific paper.

3.1.3.2 Criterion 2: Consistency with the ISO Standards on LCA

When analyzing the results from different LCA studies, it is important to understand the methodological differences between these studies. To facilitate this, it is useful to select a common framework under which all studies were performed. Since 1997, the ISO 14040-series standards have been widely used by LCA practitioners. This series of standards was revised in 2006. The ISO 14044 standard (ISO 2006b) provides a set of requirements for comparative LCA assertions (such as "recycling versus disposal" or "recycled versus virgin paper"). The most important requirements in the ISO standard following.

- Systems compared need to be functionally equivalent.
- Comparison should use consistent methodological choices for the options assessed (e.g., system boundary, allocation procedure).
- Comparison should be performed based on impact assessment (and not inventory).
- Comparison should be made on a comprehensive set of environmental categories.
- Studies must be externally reviewed.

As far as possible, the studies selected in this review fulfill this list of requirements. Note, however, that the ISO standards require that "*a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public*" (ISO 2006b, 31) and that a review panel should include at least three members. For this review, studies were not eliminated if they were reviewed by less than three people.

Case studies were retained if

- a full LCA report or a third-party report is available and the study has been peer-reviewed in conformity with the ISO 14044 recommendations; or
- the study is published in the peer-reviewed literature.

Methodological papers were retained based on their general alignment with the standards.

Although the ISO standard requires that a broad set of environmental attributes be considered, carbon footprint studies (i.e., those not based on a comprehensive set of environmental categories as required by the ISO 14044 standard, but based on carbon alone or carbon and energy alone) were also included. In addition, other types of life cycle-based studies that could help in addressing the paper recycling question were included in the review. This included, for instance, papers on material flow analysis (MFA). Studies based only on global warming and/or energy indicators have been included because, in some cases, they are relied upon to support policy making in North America (e.g. the U.S. EPA examination of the life cycle greenhouse gas impacts of municipal solid waste management), and in other cases, because they are reflective of the current global interest on carbon footprints, as illustrated by the development of several life cycle-based standards. Methodological papers describing the usage of MFA for paper recycling applications have been included to highlight the potential role of MFA in understanding wood fibre flows and providing useful inventory information for LCA studies. The other selection criteria described have also been applied to these types of studies.

3.1.3.3 Criterion 3: Date of Publication

Only case studies published after 1997 (publication of the first ISO standards) were retained. Methodological studies with an emphasis on improving the methods related to paper recycling in LCA published before 1997 were retained if the provided recommendations were consistent with the ISO standards.

3.1.3.4 Criterion 4: Specificity to Paper

This criterion was used to eliminate LCA studies where mixed waste material streams are analyzed (e.g., municipal waste containing paper) and results have not been broken down by individual waste material similar to the approach used by Villanueva and Wenzel (2007).

3.2 Summary of Methodological Studies and Literature Review

For each retained methodological study, a detailed summary was prepared and is provided in Appendix B. More importantly, the methodological studies and previously published literature reviews were reviewed to establish a preliminary list of potential key issues for the treatment of paper recycling in LCA (see Section 4.2).

3.3 Summary and Detailed Review of Case Studies

For each retained case study, a detailed summary presenting 1) the methods employed[2], 2) the treatment of key issues, and 3) the results and findings was prepared and is provided in Appendix B. They were evaluated to establish the extent to which they considered the list of key issues established from the review of methodological papers and previously published literature reviews, as well as how significant these issues were for the results of these studies.

3.4 Identification of Overarching Aspects and Significant Gaps

The preliminary list of key issues as well as the treatment of these key issues in the case studies were evaluated to establish a streamlined list of issues and to summarize the knowledge gaps in this area.

4.0 RESULTS

4.1 Inventory of Existing LCA Studies

Ninety-nine candidate studies were identified. The full list is presented in Appendix A. Classification of these studies is presented in Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4. In these figures, the total number of studies is greater than 99 because the same study can fall within more than one category.

The figures show that a large proportion of the studies on paper recycling includes case studies using a societal perspective. Fewer studies were performed in a case-specific company context. Within the candidate studies, end-of-life options were compared much more frequently than were virgin and recycled paper. Studies aimed at comparing end-of-life options for paper very often used a function centered on the management of used paper products but almost all employed a paper production function. Studies with a focus on virgin and recycled paper almost always use a paper production function.

Of the 99 documents, only 41 were retained for further analyses. The main reasons for the exclusion of the other 58 documents were 1) the study does not align with the ISO standard; 2) the document is not available in English or French; and/or 3) the document is essentially redundant with other documents included in the review. An extended summary for each of the 41 retained documents is presented in Appendix B. The relative classification of these studies is similar to that in Figure 4.1 through Figure 4.4, where all studies were considered, though the retained studies more frequently address recycling using a function centered on the paper product rather than on that of used paper.

Of the 41 retained documents, six case studies treated of global warming and/or energy indicators only and three methodological papers described complimentary approaches to LCA such as MFA.

The main findings from these studies are presented in the next sections.

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[2] Including allocation for recycling.

Note that a study by the Environmental Defense Fund (2002) is often cited in North America for its perspective on recycled paper (through a recycled versus virgin paper comparison) and was the background study for the Paper Calculator 1.0.[3] Although this study does not meet the criteria for being retained in this current analysis, a critical evaluation is also presented in Appendix B due to the frequency with which it is cited.

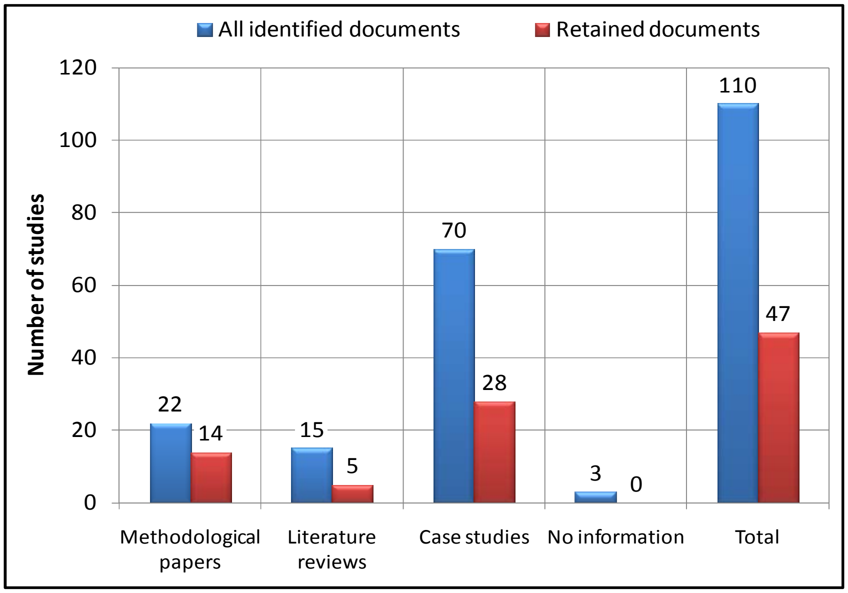

Figure 4.1 Classification of Documents by Type of Document

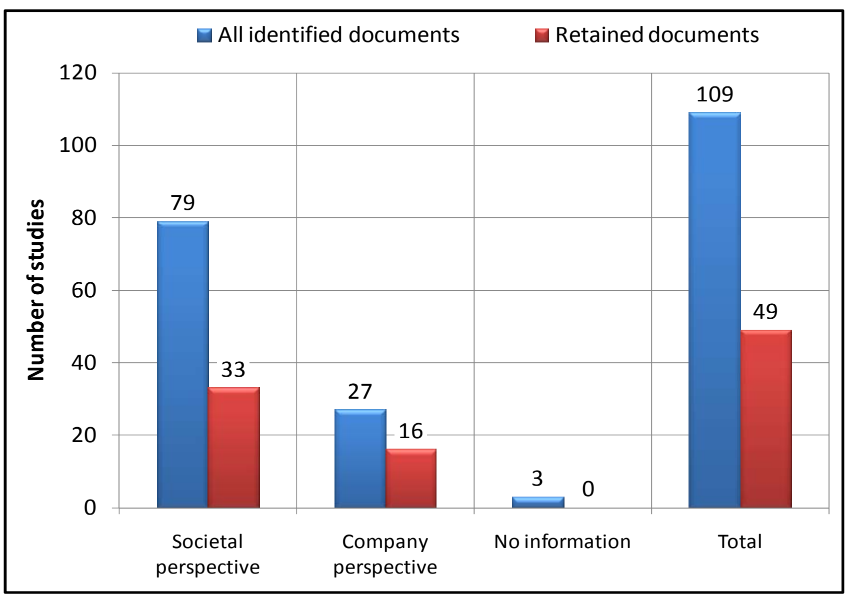

Figure 4.2 Classification of Documents by Perspective

[3] The currently available Paper Calculator is version 3.0 (http://www.edf.org/papercalculator/). Note, however, that the background information for this version is not yet available.

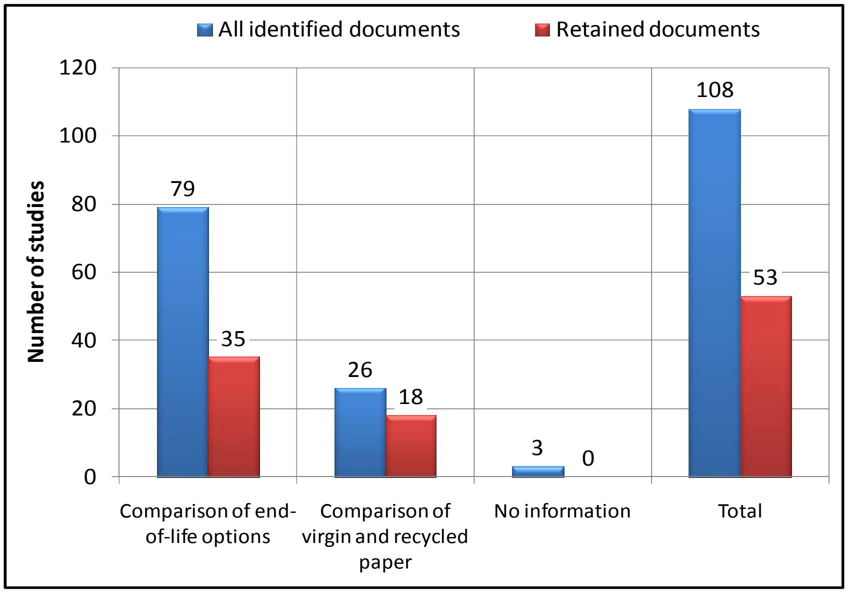

Figure 4.3 Classification of Documents by Objective

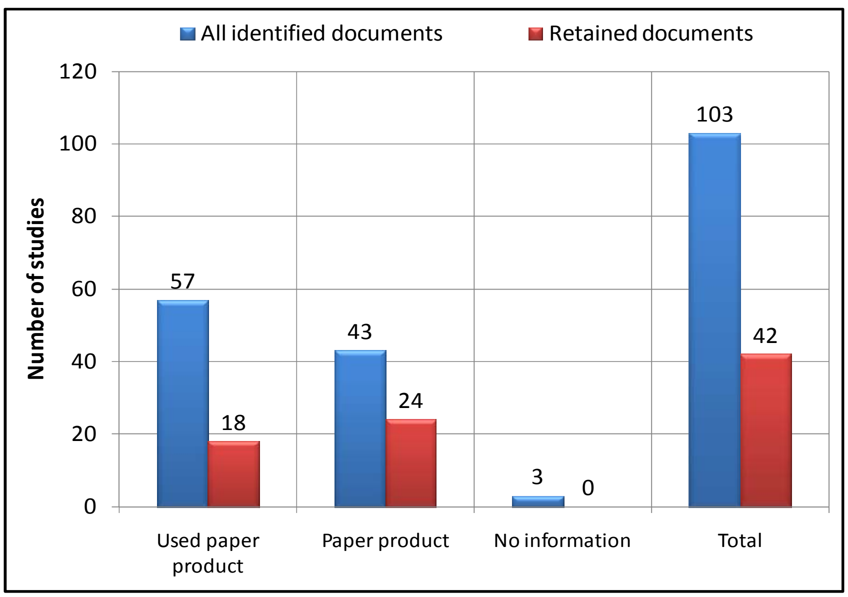

Figure 4.4 Classification of Documents by Function Analyzed

Note: In this figure, "Used paper product" is used to refer to studies for which the function was the management of used paper product while "Paper product" is used to refer to studies for which the function was the production of the paper product for a certain usage (see Table 3.1).

4.2 Summary of Methodological Studies and Literature Reviews

An extended summary for each of the retained methodological papers and previously published literature reviews is presented in Appendix B.

Based on general LCA knowledge, along with consideration of a number of studies with an emphasis on methodological considerations related to waste paper recycling (AF&PA 1996; Byström and Lönnstedt 2000; Ekvall 1996, 1999a, 1999b; Ekvall et al. 2007; Ekvall and Finnveden 2000; EEA 2006; Finnveden and Ekvall 1998; ISO 2000; Kärnä and Ekvall 1997; Tillman et al. 1994), and previous literature reviews (EEA 2006; Villanueva and Wenzel 2007; Wenzel and Villanueva 2006), several key issues were identified as a foundation for this review. These issues, which can be classified into three general categories (system boundary, impact assessment, and data), are summarized in Table 4.1. The subsequent sections present a systematic description of these key issues, primarily derived from the review of methodological and literature review papers, within each of the three general categories.

Table 4.1 Identified Key Issues Related to Paper Recycling

Category of Issues		Issue
System boundary	Forest- and wood-related	1. Forest management activities 2. Alternative use of the forest land and of the wood 3. Treatment of sawmill co-products
	Issues related to the differences between virgin and recovered fibre processing	4. Energy used in virgin and recovered fibre processing 5. Energy exports from virgin fibre processing 6. Handling of rejects at recovered fibre processing
	End-of-life	7. Landfill emissions 8. Allocation of energy exports from burning at end-of-life 9. Allocation approaches for recycling
	Other	10. Substitution effects 11. Biogenic carbon cycle
Data		12. Data gaps and quality 13. Average and marginal data for electricity production
Impact assessment		14. Land use impacts 15. Toxicity impacts

4.2.1 System Boundary Issues

One of the most important requirements for an effective comparative LCA study in alignment with ISO requirements is that the compared systems should be equivalent with respect to the goods and services they provide to society. If they are not equivalent, they should be made equivalent by adopting an allocation strategy and adjusting the system boundary of the compared system. In this context, there are several boundary-related issues in the paper life cycle that can have a significant quantitative effect on the results of any LCA-oriented comparison dealing with paper recycling. These are in the shaded boxes in Figure 4.5 and discussed in subsequent sections.

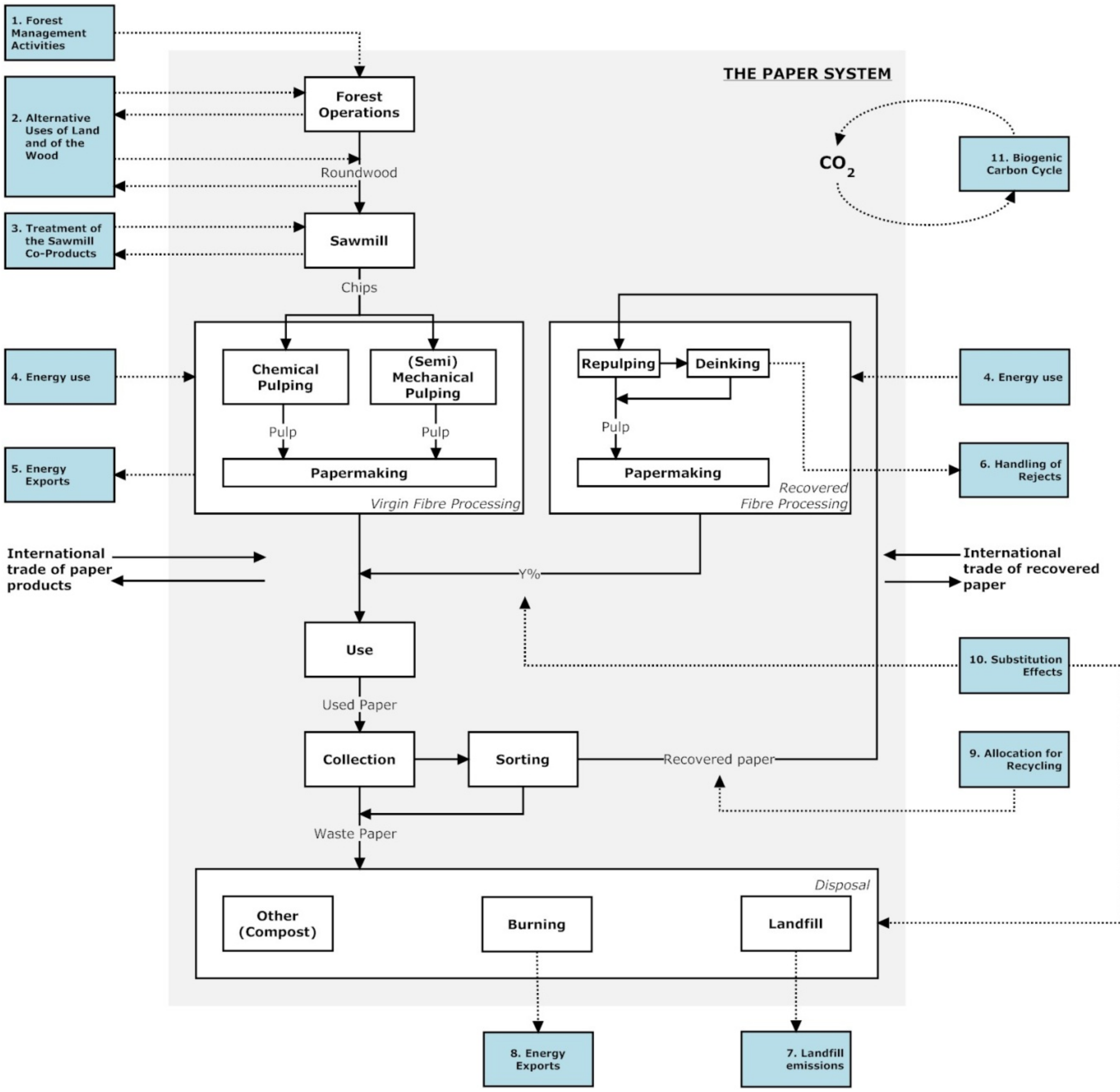

Figure 4.5 Key Issues in the Paper Life Cycle (EEA 2006)

FOREST- AND WOOD-RELATED ISSUES

Key Issue #1. Forest Management Activities

In LCA, the system boundaries should be set so as to begin with all activities required for the acquisition of raw materials and end with the final disposal of manufacturing wastes and discarded product. For wood products, the primary raw material is wood. How the boundary is set around the forest management activities can have a significant quantitative effect on LCA study results.

An assessment of the impact of forest management activities also depends on whether natural or cultivated forest is harvested. When cultivated forest is cut, it is often argued that, as the forest is replanted and brought back to the initial conditions, there is no land use change (i.e., no loss in carbon stocks or in biodiversity). However, to achieve a cultivated forest, the natural forest may have needed to be cut in the first place. As a consequence, one might argue that the cultivated forest carries part of the environmental load caused by conversion of the natural forest. This could be seen as an open-loop recycling problem where the land use change would be recycled instead of the fibre (see Key Issue #14). The choice of whether and how to allocate the land use change between the multiple subsequent uses of the land can have significant quantitative implications for paper recycling LCA applications.

Key Issue #2. Alternative Use of the Forest Land and of the Wood

All other things being equal, an increased usage of recovered fibre is likely to result in a reduced demand for pulpwood, which in turn could result in a decreased volume of wood required from forest land. Several different assumptions, which can be highly influential on the conclusions of an LCA on paper recycling, can be made regarding the alternative use of the forest and of the wood.

- No use: proportional reduction in forest management activities, the wood remains in the forest.
- Fuel: wood is still harvested but used to produce energy.
- Pulpwood: proportional increase of pulpwood consumption in other products.
- Logs: pulpwood is available for construction applications (perhaps involving extended rotation times) displacing other materials (e.g., steel and concrete).
- Conversion of the forest land into non-forest land.
- Combinations of the above.

Studies have demonstrated that the results of forest products LCAs can be significantly affected by which of these assumptions is selected and how the selection is modelled (Finnveden et al. 2005; Finnveden et al. 2000; Laurijssen et al. 2010; Moberg et al. 2005; Upton et al. 2008). Unfortunately, in many cases, the uncertainty associated with these selections and models is very large, which leads to an inability to make generalizations. This is because the responses of forest owners and forests to changes in the demand for wood are dependent on many factors which are very site-specific and involve economic and market conditions which are difficult to forecast with confidence.

Key Issue #3. Treatment of Sawmill Co-Products

Wood chips, which are the main raw material for producing virgin pulp, are often a co-product of sawmilling activities (i.e., wood that is unusable as lumber is sometimes chipped and sold for pulp production). The manner in which the environmental loads attributable to sawmilling activities are allocated between lumber (the main product of sawmilling activities) and other co-products such as chips can have a quantitative effect on the study results.

ISSUES RELATED TO THE DIFFERENCES BETWEEN VIRGIN AND RECOVERED FIBRE PROCESSING

The main raw material used for paper production is wood-based pulp. This pulp can be derived from virgin wood fibre or recovered wood fibre. The processes for virgin pulping and recovered fibre pulping are very different. To be able to interpret LCA results related to paper recycling, it is important to understand this difference.

Virgin pulping can be classified into two broad categories: chemical pulping and mechanical pulping. Of the chemical processes, kraft pulping is dominant, and produces high-strength pulp. Wood chips (produced on site or purchased) are cooked in digesters using white liquor (a solution of chemicals containing primarily sodium hydroxide and sodium sulphide). During this process, the fibres are liberated from the wood matrix by dissolving the lignin and some of the hemicellulose, resulting in a brown pulp. One of the advantages of kraft pulping is that the “black liquor” resulting from cooking, which contains inorganic chemicals and a large quantity of organic substances (primarily lignin and wood sugars) can be removed from the pulp by washing, and burned to recover energy (including both steam and electricity when cogeneration is available) and chemicals to be reused in the process. The main disadvantage is that, because the lignin is extracted, the wood-to-pulp yield is relatively low (≈50%).

Mechanical pulping processes and combinations of mechanical and chemical processes produce pulps at higher yields (80% or more) that are easier to bleach, but which have lower strength and colour stability, primarily due to the large amounts of lignin that remain in the pulp. Though largely replaced with more efficient mechanical pulping technologies, in some cases the fibres are separated by pressing the wood against a rotating "stone" (known as "groundwood" pulp). In most cases, wood chips are forced between rotating disks (known as "refiners") that mechanically separate the wood fibres. The specific equipment, process conditions, and additives can vary significantly, but in all cases, the amount of wood that is "dissolved" is small compared to chemical pulping processes like the kraft process. Mechanical pulping generally requires significantly higher electrical energy inputs than chemical pulping and does not produce black liquor solids from which biomass energy can be derived.

In recovered fibre processing, the recovered paper is mixed with hot water and repulped using hydraulic agitation. Pulping additives (e.g., wetting and fibre-dispersing agents that help break down the recovered paper into recycled pulp slurry) are sometimes added. Impurities are mechanically removed from the pulp, based on the differences in physical properties between fibres and contaminants, typically using a series of screens and centrifugal cleaners. Rejects from recycling (metal, plastic, etc.) are sent to landfill, recycled, or otherwise beneficially used. For paper grades requiring higher brightness, such as most printing and writing papers, ink removal is necessary (deinking). For this purpose, chemicals such as sodium hydroxide, sodium silicate, hydrogen peroxide, surfactants, solvents, and chelating agents may be added to the pulp. Ink is dispersed and removed from the pulp, typically in flotation cells where fine bubbles of air are introduced to a pulp suspension, moving the ink particles to the surface where they are skimmed and collected. Ink froth and rejects may be managed separately or they may be managed together with other mill wastes. In general, recovered fibre pulping requires less energy than virgin pulping. That said, recovered fibre pulping processes do not generate biomass co-products that can be used to produce the necessary energy and often need to fulfill their energy needs through the use of fossil fuels.

It is also important to understand the interactions between the virgin fibre and recovered fibre systems. Recovered fibre begins its life as virgin fibre, from harvested wood. Much of the virgin fibre that enters the paper fibre system is used repeatedly before it is finally discarded. Sometimes recovered fibre is used to make the same product and sometimes it is used to make a different product. Recycled fibre is not, therefore, separate from the industry's overall fibre system (see, for instance, http://www.metafore.org/downloads/metafore_reports_fiber_cycle.pdf).

Key Issue #4. Energy Use in Virgin and Recovered Fibre Processing

One of the most important issues in evaluating paper recycling is the energy use in manufacturing. While the energy needs for virgin fibre processing can be fulfilled, at least in part, by self-generated bio-based energy (wood wastes, spent pulping liquor), recycled fibre processing generally depends on fossil fuels (Byström and Lönnstedt 1997).

Key Issue #5. Energy Exports from Virgin Fibre Processing

Chemical pulping can produce an excess of energy that can be exported to the public power grid. This needs to be accounted for accurately, in cases where energy export is undertaken. It should be noted that the type of energy displaced (i.e., fuel type and whether it is as power or heat) by these exports can have a significant effect on the LCA results.

Key Issue #6. Handling of Rejects from Recovered Fibre Processing

Although quantitative environmental information on management of deinking waste and on its level of contaminants is not always available, the assumptions regarding these wastes can have a significant effect on LCA results, partly due to the large quantities of waste sometimes involved.

END-OF-LIFE ISSUES

Key Issue #7. Landfill Emissions

Paper partly decomposes when put into a landfill, resulting in emissions to air and water. Limited existing knowledge on landfill processes and the large variation in conditions between and within landfills make the modelling of landfill emissions very uncertain. In addition, emissions of GHGs from landfills are affected by a variety of other factors. This is illustrated in Figure 4.6.

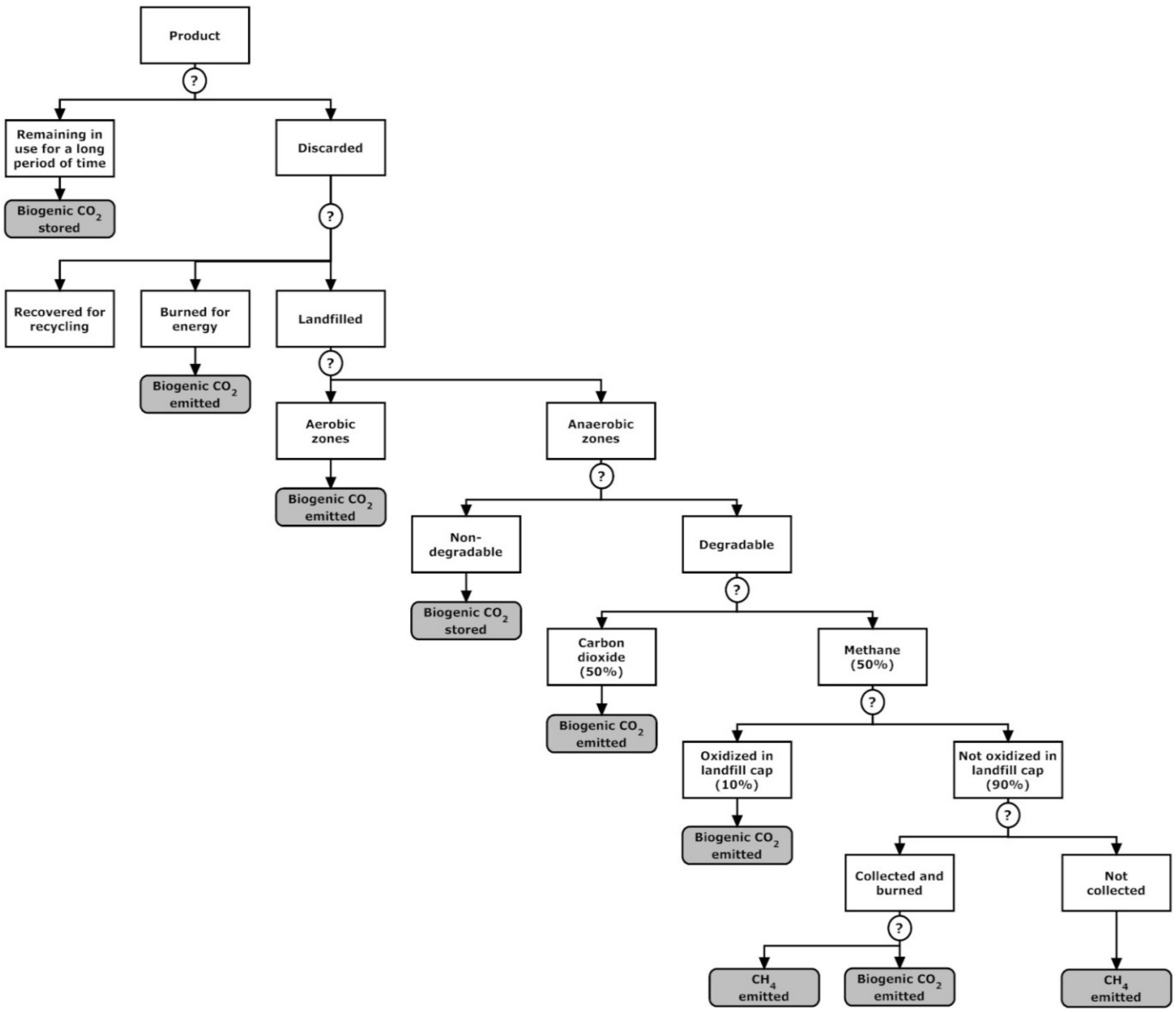

Figure 4.6 Uncertainty in Landfill Carbon Emissions

Key Issue #8. Allocation of Energy Exports from Burning at End-of-Life

Energy can be recovered when paper is burned at its end-of-life. Hence, waste paper burning fulfills two functions (waste management and energy production) and there is an allocation problem if the energy produced is used in another product system. Several methods can be used to resolve this allocation problem.

- Allocate all the energy and environmental load related to burning, to the waste management function.
- Use an allocation method to split the energy and environmental load from burning between the two functions.
- Avoid allocation through system expansion.

The method used can have significant quantitative effects on the results. In addition, in cases where system expansion is used, the assumption regarding which fuel is displaced by the energy from burning the wastes can greatly affect the results.

Key Issue #9. <u>Allocation Approach for Recycling</u>
Two types of recycling can be found in the paper life cycle: closed-loop recycling where wastes from a product system are collected and returned to be used in the same product system (e.g., repulping of conversion trim) and open-loop recycling where wastes from a product system are collected and used in another product system (e.g., recycling of office paper into tissue). Only the latter requires applying an allocation strategy. Many allocation strategies can be found in the literature. The choice among these can be critical when the objective of an LCA is to compare virgin and recycled raw material or to compare different waste management strategies for paper. The methodological papers identified in this review generally recommend using allocation strategies that do not ignore the connection between the recovery rate and the recovered fibre content.

System expansion, which consists of enlarging the boundaries of the study to include activities outside the product life cycle that can be significantly affected by an action within the life cycle (indirect effects), is the method that is most frequently recommended in methodological papers and in the ISO standard itself, especially in cases where different waste management options are compared. However, undertaking a system expansion approach requires the collection and processing of additional data on indirect effects. System expansion is justified only in cases where it can be expected to result in information that is significant to the conclusions of the study and if the uncertainty regarding those indirect effects is not too large (Ekvall 1999b).

<u>OTHER ISSUES</u>

Key Issue #10. <u>Substitution Effects</u>
There is a connection between the recovery *rate* and the recovered fibre *content* of paper products; however, this connection is not always direct. Indeed, conclusions from an LCA investigating one cannot be used directly to make conclusions about the other. A specific paper grade may be highly recovered (e.g., due to recovery efficiency or desired recovered fibre characteristics like strength or brightness), but may be reused largely in production of other paper grades. For instance, used office paper in North America is highly recovered, but office paper itself has low recovered fibre content because the recovered office paper is recycled into other paper grades (e.g., paperboard, tissue, and other printing and writing papers). Recovery rate and recovered fibre content have been studied separately and in connection. Studying an increase in only one of these without examining the effects in the other can lead to unrealistic LCA results, given the complex connections between the two. For example, such an LCA could produce results that are reliant on availability of more recovered fibre than is actually available in the marketplace, or more recycling processing capacity than currently exists.

Three key assumptions can be made related to the recovery and recycling of fibre, if system expansion is used to evaluate paper recycling. These are discussed next.

a) **Alternative use of the recovered fibre:** Knowledge or assumptions are required regarding what would happen with the fibre if it is not recovered. The main alternative uses of the fibre are use in another product, burning with or without energy recovery, or landfilling. Increasingly, recovered fibre is being exported from North America, suggesting the need to also consider alternative uses overseas. The uncertainties associated with assumptions regarding alternative uses are often large because alternative uses are highly site-specific and are impacted by economic and market conditions, which are difficult to forecast.

b) **Material replaced by recovered fibre:** Knowledge or assumptions are required regarding what material is going to be replaced. This can be virgin fibre (chemical or mechanical), recovered fibre from other sources, non-wood fibre, or non-fibre material. Similar to assumptions related to alternative uses, assumptions about replacement materials are highly uncertain because the selection of replacement material is highly site-specific and is impacted by economic and market conditions, which are difficult to forecast.
c) **Substitution ratio:** Assumptions regarding how much virgin fibre is substituted with recovered fibre can also have an important effect on LCA results.

Key Issue #11. Biogenic Carbon Cycle

The importance of comprehensive treatment of biogenic carbon is generally not recognized by currently available methodological papers that deal with paper recycling. However, the connections between climate change and the product value chain are perhaps more complex in the forest industry than in any other industry. Forests remove carbon dioxide from the atmosphere and store the carbon not only in trees, but also below ground in soil and root systems. Ultimately, the carbon in harvested wood is then either stored in forest products and landfills for a certain period or reemitted to the atmosphere. It can be returned to the atmosphere in different forms (carbon dioxide or methane), which have different impacts on the atmosphere. Forests and their carbon sequestration potential are affected by management practices, climate, and the rise in atmospheric CO_2 (Miner 2010). A simplified schematic of the biogenic carbon cycle for the paper system is illustrated in Figure 4.7.

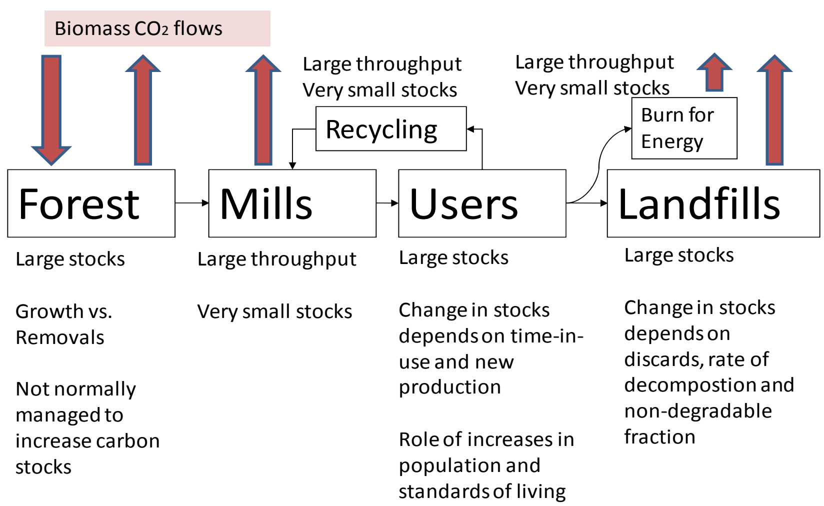

Figure 4.7 The Biogenic Carbon Cycle along the Paper System

Two accounting approaches for biogenic carbon and biogenic CO_2 are most often used in LCAs of paper products. One approach ignores biogenic carbon dioxide, assuming that any carbon dioxide emitted has previously been taken out of the atmosphere, so that the net effect on the atmosphere on a life cycle basis is zero. This approach, therefore, does not account for any imbalance that may occur (more or less carbon reemitted than taken out the atmosphere). Where potential imbalances are of interest, there are two approaches to estimating these imbalances. One is based on net flows of biogenic carbon to and from the atmosphere (called *atmospheric flow* accounting or *flow accounting*) and the other is based on net changes in stocks of biogenic carbon stored in the product system (called *stock change accounting*). Except in cases where there are flows of stored carbon across system boundaries, the two approaches give the same result.

In the case of flow accounting, one calculates all flows of biogenic carbon dioxide into the atmosphere and flows of carbon dioxide removed from the atmosphere by biomass. If biogenic carbon is removed from the atmosphere but not reemitted, this results in net emissions of biogenic carbon dioxide that are negative (i.e., there is a net removal of CO_2 from the atmosphere). If biogenic carbon is returned to the atmosphere in a gas other than CO_2, the difference in global warming potentials between CO_2 and the other gas (usually methane) is considered in the LCA.

Stock change accounting computes the changes in stocks of stored biogenic carbon. Biogenic carbon is stored in the forest, in products that remain in use for long periods of time, and in landfills when a fraction of the paper does not decompose over the long term.

As noted above, in a closed system (where all recovered fibre from a given paper system is used back in the same system), the flow and stock change approaches give the same result. However, if there is open-loop recycling in the studied system (i.e., the system imports or exports fibre to/from other systems), this will not be the case. This is because as biomass carbon in recovered fibre moves into or out of the system, it has different effects on carbon stocks in the system than it has on carbon flows from the system to the atmosphere (i.e., depending on whether it has an effect on forest carbon or landfill carbon).

These three approaches for biomass carbon accounting (ignoring biogenic carbon, flow accounting, stock change accounting) can give very different results, especially in LCA studies for which the function relates to the management of used paper products.

4.2.2 Data Issues

Key Issue #12. <u>Data Gaps and Quality</u>
While undertaking an LCA, many data gaps can arise that are not readily filled. Also, available data can be of various levels of quality. Data gaps and data quality can have a significant effect on the results of an LCA; therefore, providing commentary on the quality and sufficiency of data are a vital addition to contextualizing an LCA's results.

Key Issue #13. <u>Average and Marginal Data for Electricity Production</u>
Electricity production is often a significant contributing factor to the environmental impacts reviewed in LCAs of paper products. This is particularly true for thermomechanical pulp (TMP) production, given its reliance on purchased electricity. The choice between using data representing "average" versus "marginal" electricity consumption conditions can be expected to have significant impacts on the results when the difference in electricity consumption is an important aspect within the scenarios investigated. The difference between average and marginal electricity production is likely to be large in different regions of the Canada and the US, especially in those regions where hydropower is extensively used. While marginal data generally provide a more realistic illustration of the consequences of a decision, it is not always easy to identify the source of marginal electricity, and thus, use of marginal data may increase the uncertainty of a related LCA analysis. Also, the selection of marginal versus average depends on the time frame being considered. The marginal technology may not be the same in short- versus long-term scenarios.

4.2.3 Impact Assessment Issues

Key Issue #14. <u>Land Use Impacts</u>
Several methods have been proposed and used to estimate the environmental impacts of forestry. These methods range from a simple compilation of the land use in terms of m^2 or m^2•year to complex methods involving a large number of indicators, and no one single method has yet been universally accepted. Forestry impacts are multidimensional and not as readily quantified, and are thus difficult to describe accurately in LCA terminology. For this reason, there is a trade-off between the feasibility of

the LCA method and accuracy of description of the impacts (Ekvall 1999a). At this time, there is no consensus on how land use impacts, such as effects on biodiversity, should be included in LCA (Milà i Canals 2007). The main challenge in evaluating land use in LCA is that land is a scarce resource that is not consumed like any other resource but rather occupied and transformed, affecting its quality (Milà i Canals 2007). Evaluating change in land use quality is sometimes possible (albeit complex) at site-specific levels. Such analysis requires a level of modelling and site-specific detail generally not consistent with the broader scope of LCA.

Key Issue #15. Toxicity Impacts
For a comparison of waste management alternatives to be based on a comprehensive set of environmental concerns, as required in the ISO standard, human and ecosystem toxicity indicators should be included in an LCA. In practice, these indicators are rarely included in LCA studies because different methods usually fail to arrive at the same toxicity characterization score for a given substance (Rosenbaum et al. 2008). There are several reasons for this (Pennington et al. 2004; Reap et al. 2008). Characterization factors[4] can be based on multiple parameters such as the location of the emission, the location of the receptor, or the time period during which the potential contribution to the impact is taken into account, but in practice, LCA studies generally do not consider many of these variables. This is because an LCA can include a large number of sites, locations and time periods which can be largely unknown; thus, the current practice is to have characterization factors that are site- and time-generic. Given that toxicity impacts are so dependent on exposure conditions, LCA toxicity impact indicators can only be indicators of potential impacts, and in individual cases they may have little or no relationship to actual toxicity impacts.

Recently, a consensus method for toxicity impact assessment was developed (Rosenbaum et al. 2008). One of the main advantages of this method is its increased level of spatial differentiation. This model has not been widely tested yet and it was not applied in any of the studies included in this review.

4.2.4 AF&PA Recommendations for LCI of Forest Products

In 1996, the American Forest & Paper Association (AF&PA) published a user's guide for life cycle inventory (LCI) analysis of forest products in conjunction with the Canadian Pulp and Paper Association and other pulp and paper associations in the US, Europe, and Latin America (AF&PA 1996). This guide was the result of a collaborative effort of several international experts and consultants. While sponsored by the International Working Group, the report was prepared by Roy F. Weston Inc. (US) and PIRA (UK) with a steering committee of international experts. It was developed in parallel with the ISO standards on LCA with the intent that it would be consistent with those standards. Although the guide recognizes the need for updates to properly reflect the knowledge and experience gained, no updates have been published to date.

The guide provides recommendations on 1) functional unit, 2) system boundaries, 3) renewable nature of resources and final material, 4) renewable nature of the energy consumed, 5) solid waste management practices, 6) carbon cycle, 7) allocation for co-products and recycling, and 8) interpretation of results. In this section, the recommendations with special importance to the recycling question are summarized.

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[4] Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of an impact assessment.

4.2.4.1 System Boundary Issues

General Functional Unit, System Boundary and Allocation Issues

Comparative LCAs: In accordance with the LCA ISO standard, the AF&PA guide highlights the importance of comparing systems on the basis of the same function, measured by the same functional unit. In the case where one of the compared systems has more than one function, the guide recommends expansion of the boundary of the other system to include the additional function (i.e., system expansion by direct enlargement or by addition). For instance, in the case where paper landfilling would be compared to burning with energy recovery, the landfilling system would need to be broadened to include an equivalent energy production process.

Allocation: The AF&PA guide indicates that 1) extreme allocation procedures (i.e., allocating all or none of the environmental loads to a given product, co-product, or recovered material) are not appropriate, and 2) whenever possible, allocation should be avoided through system subdivision or system expansion. However, the guide provides few recommendations on how to do this for the different allocation problems in the forest products life cycle.

The AF&PA guide also provides recommendations for some of the system boundary issues discussed previously in this report, as noted below.

Key Issue #1. Forest Management Activities

The AF&PA guide specifies that acquisition starts with natural forest regeneration or planting and growth of seedlings. It also includes the growth and harvesting of the tree. Processes and phenomena that would occur regardless of the harvesting (e.g., emissions of volatile organic compounds, decomposition of leaves and branches that fall on the ground, etc.) or that are not related to the forest products (e.g., forest fires) should not be included. The wood source boundary should be set to include all the areas that supply wood to the manufacturing of the product investigated. The boundary should be set to appropriately account for the biogenic carbon cycle, beginning in the woodlands (more details below).

Key Issue #4. Energy Use in Virgin Fibre Processing and Recovered Fibre Processing

The guide provides a hierarchy for allocating steam consumption for a paper mill. The fuels should be used in the following order: 1) black liquor solids, 2) bark/wood wastes, and 3) fossil fuels by the following processes in the following order: a) pulping, b) chemical recovery, c) paper production from virgin fibre, and d) recovered fibre production and papermaking. The guide notes that the same kind of process thinking should be applied for cogenerated and purchased electricity.

Key Issue #5. Energy Exports from Virgin Fibre Processing

Cogeneration is often used at virgin pulp and paper mills to provide some of the electricity requirements. In many cases, some of the generated electricity is sold back to the power grid. The guide recommends that the allocation of fuels used to cogenerate electricity be based on knowledge of the cogeneration system. For instance, if electricity is generated from steam, then the electricity should be allocated the energy not available for process steam purposes. According to the guide, fuels allocated to the portion of the electricity that is sold should not be included in the forest products LCA.

Key Issue #7. Landfill Emissions

The guidelines recommend including landfills within the system boundary in a way that ensures that releases to the environment (including those produced by the degradation of the waste) are included in the inventory, while recognizing the uncertainty related to this.

Key Issue #9. <u>Allocation Strategy for Recycling</u>
The guide recommends that the number of reuses undergone by a unit quantity of fibre be estimated and that the allocable environmental loads of the virgin product system be divided between the different uses of the fibre (including the virgin use). This approach (the number of subsequent uses method) is also listed as an allocation option in the ISO 14044 standard and presented in the ISO 14049 technical report (ISO 2000), which provides examples of application for the inventory analysis in LCA.

Despite having listed the number of subsequent uses method as an allocation option, neither the AF&PA guide nor ISO 14049 provides any guidance on defining the allocable fraction of virgin production environmental loads or on how the environmental loads from recycling should themselves be allocated between the different uses of the fibre. In addition, neither provides recommendations on how this allocation approach would apply in a case where waste management practices for paper would be compared.

Key Issue #11. <u>Biogenic Carbon Cycle</u>
The AF&PA guide recommends that biogenic carbon dioxide be reported separately from fossil fuel-derived carbon dioxide and that carbon sinks be acknowledged and accounted for in the use or end-of-life (landfill) life cycle stages.

4.2.4.2 Data Issues (Issues #12 and 13)

The AF&PA guide specifies that the use of marginal versus average data, especially for energy, depends on the functional unit assessed. If the functional unit is a generic one then average data should be used. If the functional unit is based on the next increment, then marginal data should be used.

4.2.4.3 Impact Assessment Issues (Issues #14 and 15)

The AF&PA guide does not address impact assessment.

4.3 Summary and Detailed Review of Case Studies

An extended summary for each of the case studies is presented in Appendix B. The reported findings from studies reviewed in this report are presented in Sections 4.3.1 and 4.3.2. Findings are reported as presented in the studies, with no additional commentary.

4.3.1 Comparison of End-of-Life Management Options

A summary of the reported findings in the case studies addressing the comparison of end-of-life management options is presented in Table 4.2.

<u>Note that the accuracy and relative uncertainty of the comparisons of end-of-life management options presented in Table 4.2 can be significantly influenced by the key issues described above in Section 4.3.3.</u>

Table 4.2 Reported Findings for Studies Comparing Waste Management Options for Paper

Ref #	Paper Grades	Energy-Related Assumptions	Environmental Parameters	Reported Findings (valid only for the specific assumptions for each individual study)
16	Paper and board packaging	Virgin fibre processing occurs in low-carbon region (Sweden) while recovered fibre processing occurs in high-carbon region (Italy); exports of energy are assumed to displace the average Italian grid.	Total and non- renewable energy, wood consumption, global warming, acidification, and other inventory parameters	Incineration was found to result in the lowest LCA impacts for total and non-renewable energy, climate change, acidification, non-methane VOCs; recycling was found to result in the lowest LCA impacts for wood consumption, emission of particulates, water pollutants and solid wastes.
21 22	Newsprint	Electricity and steam supply are from Finland (mostly biofuels). When using more virgin wood materials, more biofuels are produced at the paper mill, and thus, the need for fossil fuels for power generation at the paper mill decreases.	Three different impact assessment methods	Landfilling was found to result in higher LCA impacts than incineration for most parameters; incineration was found to result in lower LCA impacts than landfilling if the recovered energy displaces coal use. Impact on biodiversity was recommended to be better assessed.
23	Printing and writing paper	Where surplus electricity is produced, the environmental burdens associated with the production of the same amount of electricity in the national grids where the processes take place were subtracted from the inputs and outputs of these processes.	Global warming, acidification, eutrophication, non-renewable resources, photochemical oxidant	Recycling was found to result in lower LCA impacts than landfilling.
24	Bag and sack paper	Differences in energy used for virgin and recycled fibre processing are not clear from the study; marginal technologies (fossil fuels) were assumed to be affected for any export of energy.	Global warming (IPCC) and CML method (depletion of abiotic resources photo-oxidant formation, eutrophication, acidification, human toxicity, aquatic and terrestrial toxicity	Recycling was found to reduce the impact in most of the impact categories but to cause an increase in fresh water ecotoxicity.
26 27 28	Newsprint, cardboard (corrugated and mixed)	Energy use for recycled product is from fossil fuels; energy from biomass fuels is used for virgin products; avoided electricity is from coal.	Total and non-renewable energy, non-renewable energy, abiotic resources, global warming, and acidification (others are also discussed)	Recycling was found to result in the lowest LCA impacts for total energy, global warming, acidification, SO_x and NO_x, abiotic resource, untreated wastes; incineration was found to result in the lowest LCA impacts for photo-oxidant formation, eutrophication.

Ref #	Paper Grades	Energy-Related Assumptions	Environmental Parameters	Reported Findings (<u>valid only for the specific assumptions for each individual study)</u>
32	Newsprint, containerboard and liquid paperboard	No specific information provided.	Global warming, embodied energy, smog, water use and non-degradable fraction of solid waste in landfills	The most significant benefit of recycling was found to be the reduction of the amount of material in landfills; other indicators were also found to be reduced but in the case of the global warming indicator, this was true only for the full degradation and intermediate paper degradation scenarios.
33	Corrugated board and newsprint	Corrugated board: Virgin board is consuming less fossil energy than recycled board. Newsprint: Virgin newsprint is consuming more energy (fossil and renewable) than recycled. Displaced energy is from coal.	IMPACT 2002+ and EDIP methods	Lower environmental LCA impacts were obtained for recycling, with incineration as the second-lowest LCA impacts for all paper grades and for normalized results.
35	Various	Combined heat and power from virgin system is included; displaced energy is natural gas or coal.	Global warming	The results were found to depend on technology choices for recovered fibre processing and the energy mix for virgin fibre processing.
36	Aseptic packaging	Electricity is from hydropower; kraft mills are self-sufficient.	Global warming and energy	A significant reduction of the energy requirements and global warming was found when increasing the recovery rate.
37	General	Displaced energy is from average Australian power grid (mostly fossil-based)	Global warming	Incineration was found to result in lower LCA impacts than recycling.
38	Unbleached and bleached sack paper	Recovered sacks are used for testliner production, displacing kraftliner production; energy data are based on FEFCO (FEFCO 1997); heat produced in waste incineration is assumed to replace district heat produced from other fuels (60 % light fuel oil and 40 % natural gas) and electricity, average grid.	Abiotic resource depletion, global warming, acidification, nutrient enrichment, photochemical ozone formation, aquatic ecotoxicity, human toxicity, primary energy (toxicity indicators were not used for the comparison)	For most parameters, incineration was found to result in lower LCA impacts than recycling because the energy produced by incineration was assumed to replace heat and electricity from other fossil fuels and the recycled material was assumed to replace not only virgin material, but a mix of virgin and recycled material.

Ref #	Paper Grades	Energy-Related Assumptions	Environmental Parameters	Reported Findings (valid only for the specific assumptions for each individual study)
39	Entire paper production system in Denmark (31% corrugated board and paper bags, 23% newspaper, 20% coated paper, 15% paperboard and 12% uncoated, wood-free paper)	Virgin paper used in Denmark is produced mostly in Sweden, Finland, and Germany, while recycled paper is produced locally; increased usage of recovered fibre would happen in foreign markets; virgin pulp energy is from 69% wood residuals, 20% natural gas, 8% oil and 3% coal; recovered pulp energy is from natural gas; total energy for 1 tonne of virgin paper is 21.8 GJ; total energy for 1 tonne of recycled paper is 9.6 GJ; displaced energy is marginal.	Global warming, ozone depletion, eutrophication, acidification and photochemical smog (EDIP97)	The recycling scenario resulted in the lowest LCA impacts for global warming and acidification, and incineration was found to result in slightly lower LCA impacts for the eutrophication and smog indicators.
40	Graphic paper	Substituted heat is produced from coal and natural gas, and electricity is from the average German power mix.	Terrestrial eutrophication, acidification, greenhouse gases, aquatic eutrophication, ground level ozone formation, direct harm to health and ecosystems (substance-based), use of natural areas, scarcity of fossil fuels, water consumption	Increasing the recovery rate was found to have significant benefits for most impact categories but results in an increased emission of lead; incineration with energy recovery was found to be a more effective alternative in terms of LCA impacts only in the case where coal energy was substituted.
41	Corrugated board, newspaper, office paper, magazines and third-class mail, phonebooks, textbooks	Recycled fibre processing consumes less energy than virgin fibre processing but with higher carbon intensity; fossil fuels displaced by produced energy.	Global warming	Landfilling was found to result in the highest LCA impact for GHGs except for paper made from mechanical pulp, and recycling to result in the lowest (excluding source reduction); benefits of recycling were found to be attributable to avoided landfill methane and increased stocks of carbon in the forest.

[a] Complete references are in Appendix A. [b] This is the only study that looked at waste management options for paper and used a cut-off method. All others used system expansion.

As can be seen in Table 4.2 above, studies published to date comparing recycling with other forms of waste management have tended to find that recycling appears to show more LCA-related benefits than landfilling, although it should be noted that these studies have seldom examined the large uncertainties inherently associated with key assumptions about the fate of used paper in landfills. The studies examined also suggest that it is not possible to discern whether the benefits for recycling outweigh those of incineration, or vice versa. In particular, while not noted in Table 4.2, these studies emphasize that the factors important for the environmental comparison of recycling and burning with energy recovery can be evaluated on a case-specific basis, a list of which includes

- the type of energy (i.e., fuel type and whether it is as power or heat) that is displaced by the energy generated from wastepaper;
- what material (e.g., virgin fibre), and how much, is replaced by the recovered fibre;
- in the case where recovered fibre substitutes for virgin fibre, the specific assumptions made concerning the unused pulpwood;
- in the case where recovered fibre substitutes for virgin fibre, the type of fuels used in the processing of each;
- in the case where recovered fibre substitutes for virgin fibre, the manner in which the electricity is generated for each (especially when comparisons are made related to mechanical pulp); and
- assumptions made regarding how many times wood fibre can be recovered and reused.

4.3.2 Comparisons of Virgin and Recycled Paper

Case studies comparing the environmental performance of virgin fibre- and recovered fibre-based paper are summarized in Table 4.3. Several allocation methods were used in these studies. These are further discussed in Section 4.3.3.

The performance of recycled paper versus virgin paper is highly dependent on the methodological choices made and the specificity of the case studies. This is also further discussed in Section 4.3.3.

Note that the accuracy and relative uncertainty of the comparisons of waste management options presented in Table 4.3can be significantly influenced by the key issues described above in Section 4.3.3.

Table 4.3 Reported Findings for Studies Comparing Virgin and Recycled Paper

Ref #[a]	Paper Grades	Allocation for Recycling[b]	Energy-Related Assumptions	Substitution	Environmental Parameters	Reported Findings (valid only for the specific assumptions for each individual study)
17-18	Newsprint, lightweight coated, supercalendered	Cut-off, quasi-co-product	Integrated kraft mills using mostly biomass fuels, with TMP and DIP relying on a mix of fuel	1 kg of virgin pulp is compared with 1 kg of deinked pulp (DIP)	CML, Eco-Indicator 95	The use of DIP products was found to reduce the environmental loads of paper grades compared to the use of virgin pulp; this was found to be independent of the allocation method applied.
19	Coated magazine paper	Cut-off	No information provided	1 kg of virgin pulp substitutes for 1 kg of deinked pulp.	Global warming	It was found that increasing the quantity of recovered paper did not significantly affect the carbon footprint of the studied product.
20	Newsprint, supercalendered paper, lightweight coated paper, office paper, coated woodfree paper, tissue, white lined chipboard, “return fibre chipboard”, wrapping paper, white liner, kraft-liner and fluting	System expansion to include the multiple usages of the fibre and accounting for fibre age	Excess energy from virgin pulping considered to be used in paper production; purchased electricity is from fossil fuels.	Based on fibre quality	ELU-Index[c]	A increase of use of DIP was found to • decrease the environmental load if TMP is displaced; • increase the environmental load if its substitutes virgin pulp from mills producing excess energy that can be used for drying the paper that had to be replaced by fossil fuel energy
25	Tissue paper	Cut-off, number of subsequent uses	Marginal fossil fuel energy	Not explicit	CML and IMPACT 2002+ methods	Virgin fibre resulted in lower LCA impacts for impact categories related to energy; other impact categories results were found to depend on the allocation and impact assessment methods used.

Ref #[a]	Paper Grades	Allocation for Recycling[b]	Energy-Related Assumptions	Substitution	Environmental Parameters	Reported Findings (<u>valid only for the specific assumptions for each individual study)</u>
29 30	Newsprint	Cut-off, extraction-load, system expansion	Average and marginal technologies (mostly fossil-based)	1 tonne of DIP for 1 tonne of TMP	Various impact assessment methods	Increasing DIP was found to improve most environmental indicators whatever methodological choices are made.
31	Office paper	System expansion	Implementation of the DIP process reduces the steam from black liquor that would have to be replaced by fossil fuels; the total electricity usage at the mill is increased and fulfilled by the average grid mix for that mill (80% coal, 20% natural gas).	1 tonne of DIP for 1 tonne of kraft pulp	TRACI method (all indicators)	The implementation of the DIP process was found to marginally lower LCA impacts when it was assumed that the waste paper is diverted from the landfill and detrimental if diverted from other usages (paperboard, newsprint and tissue).

Ref #[a]	Paper Grades	Allocation for Recycling[b]	Energy-Related Assumptions	Substitution	Environmental Parameters	Reported Findings (valid only for the specific assumptions for each individual study)
34	Paper and board	Closed-loop approximation and system expansion	Biomass energy is produced from virgin process that can be used in the process; recovered fibre processing is mainly based on fossil fuel energy.	1 tonne of virgin pulp substitute for 1 tonne of recycled pulp	Energy use and GHGs	Energy input was found to be lower in paper from recovered pulp and highest in paper produced from chemical pulp; virgin pulps were found to have higher feedstock use, but the bio-energy produced during pulping was found to reduce GHGs; GHGs were found to be lowest for product from chemical pulps and highest for mechanical pulps; recycling was found to lead to an increase in biomass available when compared to virgin-based production chains, if the system boundary is expanded so the same feedstock is used for each type of pulping (i.e., surplus biomass and its usage is included in the boundary); GHGs were found to be reduced for mechanical and recovered pulps and paper from recovered fibre was found to be the most favourable option.
40	Graphic paper	Closed-loop recycling	See Table 4.2	Not explicit	See Table 4.2	Using these assumptions, it was found that the higher the recovered fibre content, the lower the LCA impacts for the environmental performance of paper.

[a] Complete references are in Appendix A. [b] More information on allocation procedures is presented in Section 4.3.3. [c] The ELU-index assigns an environmental load value to emissions and to the use of non-renewable resources such as oil and coal.

4.3.3 Treatment of Key Issues in Case Studies

This section discusses how the identified key issues were dealt with in the various case studies.

Key Issue #1. <u>Forest Management Activities,</u>
Key Issue #2. <u>Alternative Use of the Forest Land and of the Wood, and</u>
Key Issue #14. <u>Land Use Impacts</u>
In the past, the inclusion of forest management activities was a potentially significant issue for paper recycling LCA applications, largely because it was not always included in the boundary of the analysis, rendering comparisons extremely difficult. All case studies retained for this review included forest management activities within the boundary of the analysis, suggesting that this is no longer an issue.

What continues to be an issue is whether and/or how land use impacts are treated for recycling applications. Most case studies reviewed did not address this question. Some studies circumvented the issue by assuming that the same amount of wood is harvested for all compared scenarios and that the surplus wood would be used for energy production. One study (Tiedemann 2001) assessed the impact on land use of recycling by evaluating how much land was modified from one level of land quality to another, where land quality levels were defined based on a complex set of indicators. Also, the US Environmental Protection Agency (USEPA 2006) estimated the impact on forest carbon stocks of recycling using an empirical simulation model to estimate and predict carbon budgets in US forest ecosystems (FORCARB II). The only land quality metric that was analyzed in this study was the carbon stocks.

A forest-specific method has been developed to assess the land use impacts of forest operation in a life cycle study of paper products (Axel Springer Verlag AG et al. 1998a). This method is based on the premise that there is a direct link between land use activities and potential effects, and that the more sustainable management practices are, the less damage caused. Hence, instead of measuring damage, the method assesses whether sustainable forest management practices are present or absent. Although the importance of land use impact for different types of pulp (virgin and recovered) was assessed in the case study provided by the authors, the effect of recycling on land use impacts was not directly evaluated making it difficult to comment on the usefulness of the method in this context.

Key Issue #3. <u>Treatment of the Sawmill Co-Products</u>
The choice of allocation method for sawmill co-products (e.g., system expansion, mass allocation, or economic allocation) has been identified as a potentially significant issue for paper recycling-related LCAs (Villanueva and Wenzel 2007). The implication of this choice for the results was not assessed by any of the case studies reviewed. In addition, it is expected that if system expansion were to be used, assumptions about what is avoided could have an effect on the results.

Key Issue #4. <u>Energy Use in Virgin Fibre Processing and Recovered Fibre Processing</u> and
Key Issue #5. <u>Energy Exports in Virgin Fibre Processing</u>
The type and quantity of energy (i.e., fuel type and whether it is as power or heat) used during virgin and recovered fibre processing clearly has a significant influence on the results of LCAs related to paper recycling. For instance, one case study found that the benefits associated with the use of recovered fibre to displace mechanical pulp are largely dependent on the greenhouse gas intensity of purchased electricity (Byström and Lönnstedt 1997).

In addition, energy is often exported from virgin fibre processing, especially from chemical pulping operations. Often, it was not clear how this was dealt with in the case studies. However, it is reasonable to believe that assuming that if fossil fuel-based energy, and more specifically coal-based energy, were displaced, this would produce significant benefits from virgin pulping – while an assumption that the displaced energy were from biomass sources or wastes would produce limited benefits. The magnitude of the benefits is difficult to determine without analyses conducted in this specific context.

Key Issue #6. Handling of Rejects from Recovered Fibre Processing

Given that recovered paper processing involves the removal of insoluble contaminants, a significant aspect of paper recycling is the generation of waste solids. The fraction of recovered paper that is lost along with these rejects is highly dependent on the relative contamination in the recovered fibre input material and the processing equipment used. Increasing the recovery rate for wastepaper may lower the quality of recovered paper and thus, potentially lead to an increase in the generation of rejects. Most of the rejects from recycling and deinking processes end up as waste and are ultimately disposed of in landfills or, in some cases burned. These rejects can have a high content of inorganic substances [e.g., metals (NCASI 2008)], as can some deinking mill process effluents (European Commission 2001), and thus can significantly affect LCA impact assessment results, when these substances are modelled.

The issue of inorganic substances in rejects and/or mill effluent was rarely addressed in case studies, perhaps because those substances are important for toxicity-related impact categories, which are highly uncertain (see Section 4.2.3). However, the very few case studies that did include toxicity categories in their evaluation found that there was potentially some increase in the impact categories related to toxicity. That said, the challenges in modelling these issues do not allow for firm conclusions in this area (see Key Issue #15 below).

Key Issue #7. Landfill Emissions and
Key Issue #11. Biogenic Carbon Cycle

The treatment of landfill emissions and of biogenic carbon is potentially significant to the results from applying LCA to paper recycling, especially for the global warming impact indicator. The extent to which different biogenic carbon accounting approaches are applied is presented in Figure 4.8. Assumptions made regarding paper degradation in landfills are presented in Figure 4.9.

In some cases, information on how biogenic carbon and landfill emissions are dealt with is not available in the description of the study. In most cases, biomass carbon was accounted for by following biomass carbon flows (flow accounting) or biomass carbon was ignored ("no accounting") These two methods vary significantly, in that flow accounting can account for carbon storage and the other does not. Note, however, that the flow accounting approach can be used in such a way as to not account for carbon storage, if it assumed that all carbon is degraded and there are no other carbon sinks in the life cycle (i.e., all carbon uptake is reemitted and hence the net emission of biogenic carbon dioxide is zero).

A few studies (Finnveden et al. 2000, Grant et al. 2001, Moberg et al. 2005) investigated the effect of various assumptions regarding paper degradation in landfills, through sensitivity analyses. The analyses showed that the nature of the assumptions used had a quantitative effect on the global warming indicator results. Where used paper is landfilled, other LCA impact indicator results (e.g., smog) are also highly dependent on the extent to which paper degrades. This finding is especially significant in light of the experimental data that suggest that only a fraction of paper products decompose in landfills and that this fraction is highly dependent on the paper grade (USEPA 2006). Given the documented sensitivity of LCA results to the assumptions about paper degradation, and the uncertainty in those assumptions (especially where the variability between paper grades is not considered) the information related to this finding is subject to considerable uncertainty.

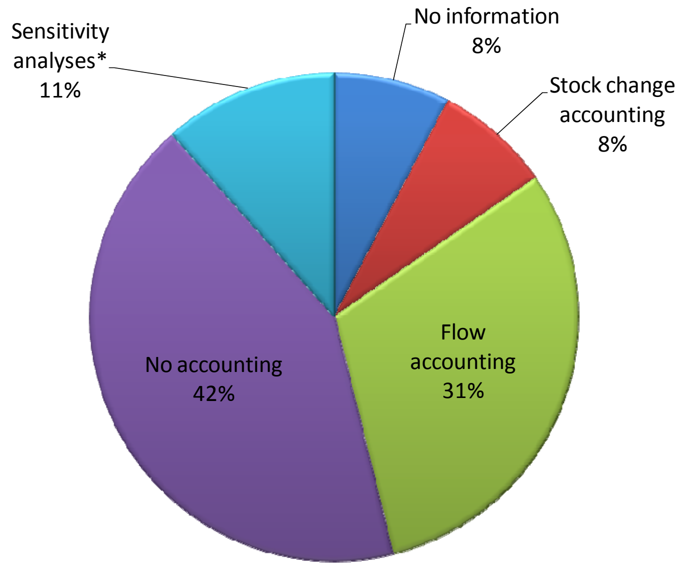


Figure 4.8 Biogenic Carbon Accounting Approaches Used in Case Studies
*Sensitivity analyses were performed on using no accounting or flow accounting.

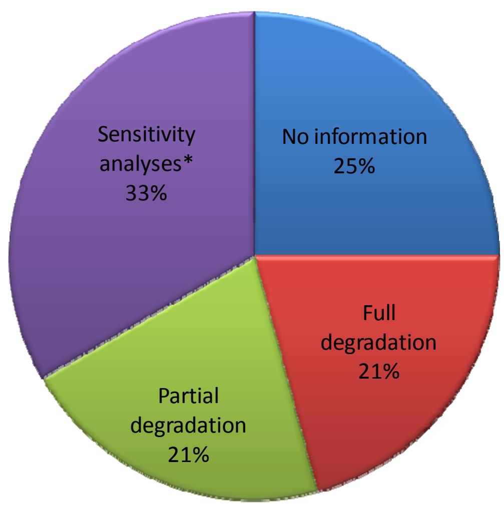


Figure 4.9 Assumption Made regarding Paper Degradation in Landfills
*Sensitivity analyses were performed using different degradation percentages including full degradation.

Key Issue #8. Energy Exports from Burning

Most of the reviewed case studies assumed that the energy substituted with energy produced by burning paper waste is from fossil fuel-based sources and many of the studies concluded that burning used paper with energy recovery often, but not always, results in enhanced LCA results compared to recycling. However, most case studies (in cases where the information was provided) assumed that the recovered fibre is reused only once. It was shown in one study that considering multiple usages of recovered fibre can reverse this conclusion (Nyland et al. 2003).

A previous literature review that included older studies (EEA 2006, Villanueva and Wenzel 2007, Wenzel and Villanueva 2006) showed that if it is assumed that bio-energy or energy from other wastes is displaced, then used paper recycling is the option that produces lower LCA results.

Key Issue #9. Allocation Strategy for Recycling

Many allocation strategies can be used for recycling. These include system expansion, the closed-loop approximation, the ISO 14049 number of subsequent uses method (ISO 2000), the quasi-co-product method, the cut-off method and the extraction load method. A general description of these methods and how they were applied in case studies is discussed in this section.

System Expansion

System expansion can be performed either by “direct system enlargement” or by subtraction of the “avoided burden”. System expansion by direct system enlargement involves expanding the boundary to include the additional functions in the system. In the avoided burden method, the surplus functions are eliminated by subtracting equivalent mono-functional systems to obtain a functional unit that is based on one function only. Together with system subdivision[5], system expansion is the preferred option under the ISO 14044 hierarchy for allocation strategies, primarily because it is a way to avoid allocation. The use of system expansion is also frequently justified as a way to generate a comprehensive picture of the actions that may affect the potential environmental impacts from production of paper, if applied properly.

System expansion, in particular by using the avoided burden method, is the most frequently used method when the objective of an LCA is to evaluate different end-of-life options for paper. That said, it has frequently been applied in a manner that does not preserve mass and energy balances, as illustrated below. Direct system enlargement has also been used, in some cases, where the objective was to compare virgin and recycled paper.

When applying the avoided burden approach to deal with fibre recovery for recycling at the end-of life, a number of papers have enlarged the system boundary to include the processing of the recovered fibre and the avoided virgin production. The rationale behind this way of applying the avoided burden method is to eliminate the surplus function (i.e., the undesired function), as illustrated in Figure 4.10. In this figure, the function of interest, in this case the management of used paper, is obtained by including the recovered fibre processing process in the system boundary and subtracting an equivalent avoided raw material function (i.e., virgin material production).

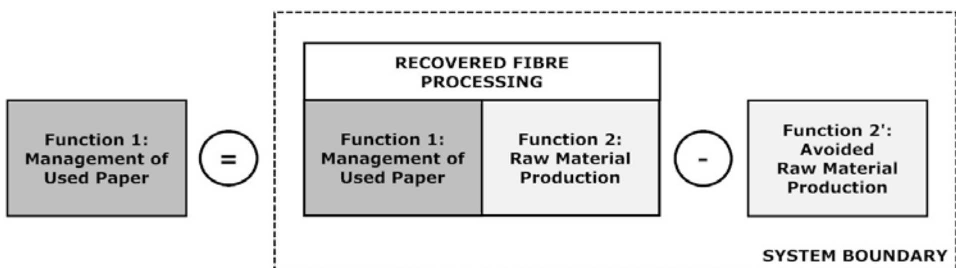
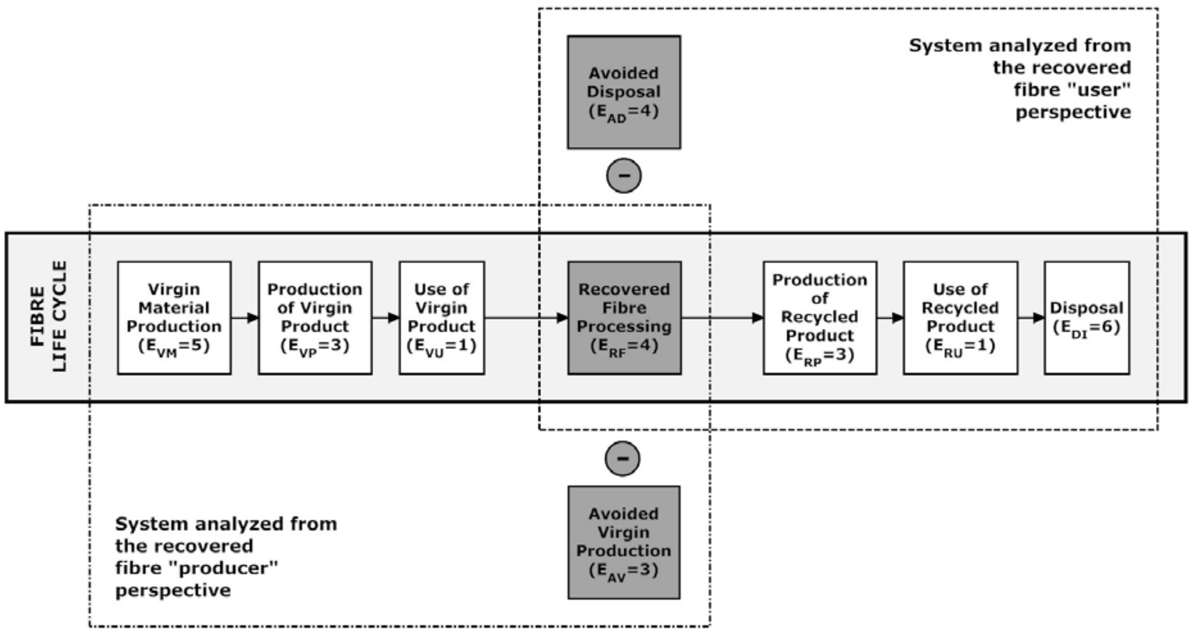


Figure 4.10 Application of the Avoided Burden Method in Reviewed Case Studies, To Deal with End-of-Life Recovery for Recycling

No published case studies using the avoided burden approach for the utilization of recovered fibre as a raw material were found in the literature. However, if this method is applied exactly the same way to the recovered fibre used as a raw material, care is needed to ensure mass and energy balances are conserved as required by the ISO 14044 standard (ISO 2006b, 14): “*The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before*

[5] Way of avoiding allocation by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes.

allocation"[6]. An example of application of the avoided burden method where mass and energy balances are *not* preserved is presented in Figure 4.11. There are multiple approaches that could be used to make this illustrated allocation additive, thereby meeting the ISO requirement; however, these approaches will not be presented here, given that no one approach is more accurate than another.



In this figure, E_{XY} represents a **hypothetical** environmental load value for each of the unit processes in the fibre life cycle. The total environmental load, E_{FC}, for the fibre life cycle can be calculated as follows:

$E_{FC} = E_{VM} + E_{VP} + E_{VU} + E_{RF} + E_{RP} + E_{RU} + E_{DI} = 5 + 3 + 1 + 4 + 3 + 1 + 6 = 23$

In order to attribute specific environmental loads to the system producing the recovered fibre (upstream system) and to the system using the recovered fibre (downstream system) the avoided burden method can be applied to the recovered fibre processing that is shared between the upstream and downstream systems. Indeed, it provides an end-of-life management function to the upstream system and a raw material production function to the downstream system.

At face value, it would appear that the environmental load attributable to the system producing the recovered fibre, E_{PR}, can be calculated as follows:

$E_{PR} = E_{VM} + E_{VP} + E_{VU} + E_{RF} – E_{AV} = 5 + 3 + 1 + 4 – 3 = 10$

And that the environmental load attributable to the system using the recovered fibre, E_{US}, can be calculated as follows:

$E_{US} = E_{RF} + E_{RP} + E_{RU} + E_{DI} – E_{AD} = 4 + 3 + 1 + 6 – 4 = 10$

However, the sum of the environmental load attributable to the producer and to the user of recovered fibre (10 + 10 = 20) is not equal to the environmental load attributable to the entire fibre life cycle (23) and thus the mass and energy balances are not preserved.

Figure 4.11 Example of Application of the Avoided Burden Method Where the Mass and Energy Balances Are Not Preserved

[6] Although this statement specifically refers to "allocation", system expansion is one of the first options of the stepwise procedure to deal with allocation problems. Thus, this requirement is also applicable to system expansion.

A key concern with the avoided burden method, as applied in the case studies in this literature review, is that it has been applied in a manner that assumes that only the recovered fibre processing itself is shared between virgin and recovered fibre products, as illustrated in Figure 4.11. The ISO standard specifies that open-loop recycling deserves additional elaboration because it *"may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system"* (ISO 2006b, 15). This means that, for instance in Figure 4.11, the virgin material production and disposal processes would *also* require an allocation strategy to be applied, for the allocation in this figure to meet ISO requirements.

In the case studies using direct system enlargement, two different approaches have been taken: an approach in which the boundary is expanded to account for the function attributable to one single usage of the recovered fibre (i.e., production of raw material for papermaking) and another that expands the boundary to the multiple usages of the recovered fibre. The second approach is a more accurate model of the wood fibre system, but brings more uncertainty to the results of the analysis. It was shown that including the multiple usages of the fibre can change the results (Nyland et al. 2003). Note that the case studies that used the avoided burden format of system expansion all considered only one usage of the recovered fibre.

Finally, both forms of system expansion can often be based on inaccurate assumptions (Ekvall 1999b). In the reviewed studies it is often assumed that a specific grade of used paper is recovered and reused in the production of the same grade of paper or in only one other grade of paper. This assumption may be inaccurate. In addition, in order for the picture of environmental consequences to be truly comprehensive, it is important to consider not only that a fibre can be reused multiple times, but that its quality degrades with each use. This can be done by applying LCA in combination with broader system analysis tool such as material flow analysis (MFA). However, such an approach may lead to very complex process chains.

Closed-Loop Approximation

The closed-loop approximation is a way to avoid allocation by assuming all recovered material is reused within the same product life cycle. By avoiding allocation, this approach falls within the preferred option hierarchy in the ISO 14044 standard. In this approach, the product system supplies secondary raw material to a pool and is supplied with secondary material from the pool. If the import and export of secondary raw material between the pool and the product system are equivalent, there is no problem in modelling the product system as a closed-loop system. If there is a net input or output of raw materials, this should be dealt with using an open-loop procedure because there is an allocation problem concerning the effects of these exports or imports. If system expansion were used, the boundary would be expanded to include the potential effects. The closed-loop approach is an attempt to approximate system expansion by adjusting the technology split of virgin production and recycled production within the boundary of the studied product, i.e., without expanding the boundary. This assumes that the environmental profiles of virgin production and recycling production are similar in both the product-specific system and the rest of the market, and that the inherent properties of the virgin and recycled pulps are identical or similar. More information on this method is in Appendix B.

The closed-loop approximation was used in the case of newspapers in Helsinki (Dahlbo et al. 2005), and various paper grades in the US (USEPA 2006). The limitations of this approach were recognized in both studies. In practice, closed-loop recycling is a good approximation for very few paper grades, at least in North America. For instance, in 2006, the recovered paper utilization rate for US printing and writing paper production was 6.4% (AF&PA 2007) but its recovery rate can be as high as 70%, depending on the grade that is recovered. Recovered printing and writing papers are largely used in paperboard and tissue production.

Number-of-Subsequent Uses Method

This method, listed in ISO 14044 and described in the ISO 14049 technical report (ISO 2000), shares the burden of virgin material production between the virgin and recycled systems based on the number of uses of the fibre. The number of uses is calculated based on the recovery rate and the production yields of recycled products. It represents the number of total product units (virgin + recycled) per unit of virgin product. Although the ISO technical report illustrates how to allocate virgin fibre-related burdens, it does not describe how to allocate the burden of the recycling processes themselves. More information regarding this method can be found in Appendix B.

This method has been described as pivotal for recycling allocation in the case of paper products because these products are constructed around a basic module, the fibre, that is recycled into multiple products (AF&PA 1996). This method was applied for a study for which one objective was to compare virgin and recycled pulp for tissue production. The author justified its usage as follows:

> *"The modelling of open loop recycling of paper products to tissue paper is complex, since used tissue paper is discarded where recycled paper can be recycled, recovered and recycled a number of times. Therefore, it is considered that some account of the environmental impact associated with the loss of a fibre resource from other recycling systems should be made. There is no widely accepted method for accounting for the reduction of fibre availability due to its loss through tissue manufacture. ISO14049 presents a solution through the partial allocation of the environmental impact of the waste paper's first life to the waste paper that is collected for tissue production. The allocation depends on the number of uses for which the fibre is recycled and the recovery rate for waste paper for recycling"* (ERM 2007, 10).

Quasi-Co-Product Method

The quasi-co-product allocation method considers the entire life cycle of the fibre as one process for which several quasi co-products are produced (one per fibre use). For instance, if the fibre is reused twice, then there are three quasi-co-products: the virgin product and the two recycled products. The total environmental load of the entire aggregated process (life cycle of the fibre) is summed up and allocated to the quasi-co-products. Classical process allocation rules can be used. This method was used in one case study to compare various fibre types (including virgin and recycled) for the production of newsprint and magazines (Axel Springer Verlag AG et al. 1998b). In this study, the total load of the fibre life cycle was allocated based on the mass of the different co-products. Although not specifically discussed in the ISO 14044 standard, this method is a variation of the ISO 14049 number of subsequent uses method, modified so as to share the load of the recycling and end-of-life processes between the different products. Using mass allocation, all the products (virgin and recycled) in a given fibre cycle have the same environmental load per unit.

Cut-Off Method

The cut-off method assumes that each product in the fibre life cycle is only responsible for the environmental impacts with which it is directly associated. Using this approach, the recycled material does not carry any load from virgin material production. This method is not presented as an option in the ISO 14044 standard. The cut-off method is simple to use but it dissociates the recycled fibre with its upstream environmental profile and therefore may be less realistic.

This method was used in a few case studies that focused primarily on comparing virgin and recycled paper. Use of this method was justified by authors of the studies. In one case study, the method was justified as a way to directly compare the efficiency of the virgin fibre and recycled fibre processing processes (Axel Springer Verlag AG et al. 1998b, 20). However, the authors recognized that the method is biased, and in the case where *"virgin pulp is produced for the purpose of multiple use, the burdens of the production have also to be allocated to the DIP processes as well as the burdens of the downstream processes at the end of the life cycle have to be allocated to the production of the fresh fibre"*. For this reason, another allocation method was also used (see Quasi Co-Product Method, above). Other potential justifications for using this method included the elimination of the uncertainty regarding the number of times that a material is recycled, where the investigated product is located in the fibre life cycle, and how the original virgin fibre was processed (Gaudreault et al. 2010). In some other studies, the justifications were not explicit.

This method was also used in one study with the objective of comparing different recovery rates for Tetra Pak (Mourad et al. 2008).

Extraction-Load Method

This method, which is not discussed in the ISO 14044 standard, assumes all material will end up as waste and that final waste management is an inevitable consequence of material extraction from the environment (Ekvall and Tillman 1997). It allocates the virgin production and end-of-life loads entirely to the virgin product and recycling loads to the recycled product. This method assigns relatively lower loads to recovered material in cases where the environmental load of recycling is less than the combined environmental load of virgin production and final waste management. This method was used only for sensitivity analysis purposes in one case study included in this review (Gaudreault et al. 2010).

Comparison of Methods

Only a few case studies compared different allocation methods for recycling and always in the context of using deinked pulp (DIP) versus virgin pulp. Different findings were observed in each of these studies. Given the limited number of comparisons of various allocation methods and the limited scope of the comparison performed, it is difficult to make generalized conclusions on the significance of this choice for the results of an LCA on paper recycling.

In one case study, the cut-off and quasi-co-product allocation methods were compared in the context of newspapers and magazines (Axel Springer Verlag AG et al. 1998b). The quasi-co-product allocation method generally gave higher scores for DIP and reduced the scores for virgin pulp. However, use of this method versus use of the cut-off method did not affect the overall life cycle results for newspapers and magazines.

In a second case study, the cut-off and number of subsequent uses methods were compared for tissue production (ERM 2007). The choice of the allocation method changed the result of the virgin and recycled paper comparison for some of the indicators considered in the analysis but not all.

Finally, the cut-off and extraction-load methods were compared in the context of a case study that analyzed the effects of increasing DIP consumption at a newsprint mill (Gaudreault et al. 2010). This study found that, for the products studied, the extraction-load model gives significantly more benefits to the products with high recovered fibre content than the cut-off method.

Key Issue #10. Substitution Effects

Recycled paper and virgin paper do not have the same quality or functionality (Villanueva and Wenzel 2007). As fibres are reused, they become shorter and after a certain number of cycles (4-8, see Metafore Fibre Cycle information at http://www.metafore.org/downloads/generic_cycle.pdf) they become too short to be of further use in papermaking, and can no longer be retained in the pulp slurry within the processing system. Hence, longer fibres (virgin) have to be added into the papermaking system to retain quality. Figure 4.12 illustrates this for a theoretical closed-loop recycling system for different yields (i.e., remaining original fibre in recovered fibre pulp as a fraction of the fibre in the unprocessed recovered paper). The figure shows that in a closed-loop system 10-50% virgin fibre is required to sustain the fibre cycle. Therefore, waste paper cannot sustainably substitute for virgin paper at a 1:1 ratio, though this was almost always assumed in the case studies reviewed.

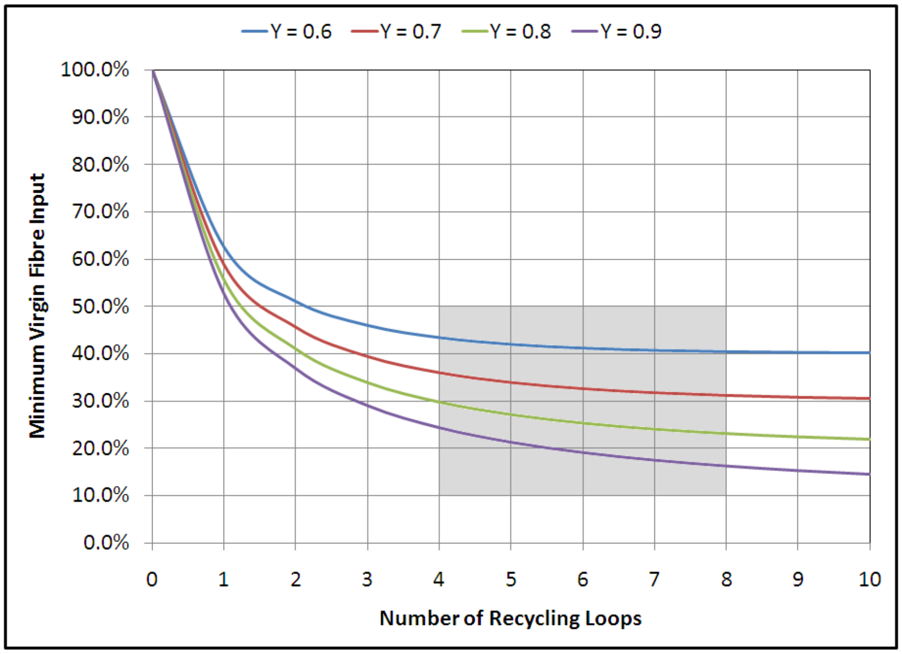


Figure 4.12 Theoretical Minimum Virgin Fibre Input for Closed-Loop Recycling with Various Recycling Yields

Also, there is a connection between the recovery rate and the recovered fibre content of paper products; however, this connection is not always direct. In some case studies, conclusions from an LCA investigating one were directly used to make conclusions about the other. This is not appropriate given the complex connections between the two.

Key Issue #12. <u>Data Gaps and Quality</u>
Most of the studies used data specific to their context and discussed data gaps and quality. This issue was not found to be significant except for toxicity-related impacts.

Key Issue #13. <u>Average and Marginal Data for Electricity production</u>
Use of marginal versus average data for electricity production has been identified as a potentially significant issue in LCA studies involving paper recycling (see Section 4.2.2). This was almost never addressed in the studies reviewed. If the average and marginal production processes are assumed to be significantly different, this could have an influence on LCA study results. In a many of the studies reviewed, both the average and marginal technologies for energy production were assumed to be fossil-fuel based.

Key Issue #15. <u>Toxicity Impacts</u>
As mentioned previously, toxicity impacts are rarely addressed in LCA studies. The significance of toxicity impacts in the context of recovered fibre processing was discussed previously under Key Issue #6. However, potentially toxic substances can be emitted in several places in the paper life cycle from virgin or recovered fibre, as illustrated in various studies aimed at characterizing effluents from the pulp and paper industry [e.g. see the *Development Document for Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category* (USEPA 1993)]. As illustrated by these studies, there is still a lot of uncertainty in quantifying potential toxicity-related life cycle impacts. Hence, at this time, no study results can be seen as accurately characterizing this issue.

5.0 DISCUSSION OF THE RESULTS AND CONCLUSIONS

The objectives of this study were to perform an inventory of LCA studies dealing with paper recycling to 1) summarize proposals for improving the methods related to paper recycling in LCA and key issues that were identified for paper recycling LCA applications; 2) discuss the treatment of key issues in case studies and the implications of this treatment to the results; and 3) identify the overarching aspects and knowledge gaps that have a significant effect on results of LCAs related to paper recycling.

Ninety-nine relevant studies were initially identified, from which a large proportion were comparisons of end-of-life options for paper (landfill, burning with energy recovery, recovery for recycling) using a societal perspective. Fewer available analyses had been performed in a case-specific company context or compared the use of virgin and recycled fibre for paper production. Only 41 studies were reviewed in detail based on a predefined set of criteria.

Based on the methodological papers and previously published literature reviews, 15 issues (11 system boundary-related, 2 impact assessment-related and 2 data-related) were identified as being of potential significance to paper recycling LCA results: 1) modelling of forest management activities; 2) alternative use of the forest land and of the wood; 3) treatment of sawmill co-products; 4) energy use during virgin and recovered fibre processing; 5) energy exports at virgin fibre processing; 6) handling of rejects from recovered fibre processing; 7) landfill emissions; 8) energy exports related to burning waste paper; 9) allocation strategy for recycling; 10) substitution effects; 11) biogenic carbon cycle; 12) data gaps and quality; 13) average and marginal data for electricity production; 14) land use impacts; and 15) toxicity-related impacts.

This review of LCA case studies (which included both full LCAs and LCAs based on carbon only or on carbon and energy) in relation to these 15 issues led to the identification of the following seven overarching issues that drive the results of recycled fibre-related LCAs or for which there is still too much uncertainty to fully understand their potential effect on LCA results:

- impact of land use and alternative usage of the forest area;
- the type of energy (i.e., fuel type and whether it is as power or heat) used during virgin and recovered fibre processing;
- the type and amount of energy displaced when burning waste paper;
- current capabilities of toxicity-related modelling for LCA impact indicators;
- assumption regarding the degree of paper degradation in landfills and the approach used for modelling of biogenic carbon dioxide;
- the selected allocation procedure for recycling, in cases where virgin and recycled paper are compared; and
- recycled-to-virgin fibre substitution ratio.

Overall, the existing knowledge on LCA and paper recycling does not allow for general conclusions to be made regarding the environmental superiority of using recycled or virgin fibre for paper production.

That said, many of the reviewed studies resulted in findings that suggest a lower LCA profile for paper recovery for recycling over landfilling as a used paper end-of-life option. The applicability of this finding, however, is limited given the extent to which it depends on assumptions regarding paper degradation in landfills and the methods used to account for biogenic carbon. Also, the weakness of current toxicity-related impact assessment modelling approaches could be a limitation to this finding.

The environmental analysis of recovery for recycling over burning for energy did not produce findings that can be generalized, primarily due to this question's sensitivity to the key issues mentioned above.

6.0 RECOMMENDATIONS

There is opportunity to improve the consistency and transparency of the treatment of paper recycling within LCA. More specifically there is a need for better understanding of the actual implications of using more recovered fibre in paper and paperboard products. This is a complex problem that requires an understanding of fibre flows across sectors and countries. Some elements of solutions could include the following:

1. the development of a fibre flow model that identifies the fibre flows within and between industry sectors and countries, including technical and market constraints on fibre flows;
2. the regionalization of that model to allow it to address regional factors important to environmental performance (especially product mix, mill energy supply mix, and fuels used to produce electricity on the grid);
3. the development of a regional average gate-to-gate data set for each paper and paperboard grade;
4. the development of pulping "process" models for pulping (virgin and recovered fibre) and papermaking, reflecting the major mill types in different regions; and
5. the combination of process models with upstream and downstream models to yield a cradle-to-grave model capable of identifying the general types and magnitudes of effects that would accompany changes in recovered fibre use.

Other recommendations include the development of enhanced impact assessment methods for toxicity and land use impacts or the application of tools capable of analysing those effects.

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APPENDIX A

COMPLETE LIST OF DOCUMENTS CONSIDERED

A.1 LIST OF DOCUMENTS RETAINED FOR FURTHER ANALYSIS

Study Included	Classification	Short Summary (taken directly from the studies)
1. METHODOLOGICAL PAPERS		
S1. American Forest & Paper Association (AF&PA). 1996. *Life cycle inventory analysis user's guide - Enhanced methods and applications for the forest products industry*. Washington, DC: American Forest & Paper Association.	1A/Ba/bii	This document constitutes a user's guide for performing an LCI in the Forest Products industry. It includes recommendations for recycling.
S2. Byström, S. and Lönnstedt, L. 2000. Paper recycling: A discussion of methodological approaches. *Resources Conservation and Recycling* 28(1-2):55-65.	1A/Ba/bi	In this paper, the authors argue that an analysis of the trade-offs between energy and material uses due to waste paper recycling, and increased of purchased energy by the industry requires a systems analytical approach including the different production lines, fibre flows and alternative uses of the fibre rather than a life cycle analysis with allocation methods. They show that allocation methods sometimes used in life cycle analyses do not give a good approximation.
S3. Ekvall, T. 1996. *Key issues in the assessment of wood fibre flows*. NORDPAP/DP2/20. Göteborg, Sweden: CITekologik. S4. Ekvall, T. 1999. Key methodological issues for life cycle inventory analysis of paper recycling. *Journal of Cleaner Production* 7(4):281-294.	S3. 1. General S4. 1A/Bai	In these publications, Ekvall presents key issues for LCA applied to the Forest Products industry, including recycling.
S5. Ekvall, T. and Finnveden, G. 2000. The application of life cycle assessment to integrated solid waste management. Part 2 - Perspectives on energy and material recovery from paper. *Process Safety and Environmental Protection* 78(B4):288-294.	1A/Bai	The comparison between recycling and incineration with energy recovery is often in focus. Different studies have arrived at different conclusions due to differences in the methods applied and assumptions made in the life cycle inventory analysis (LCI). Key factors for the LCI results include what energy is replaced by incinerated waste paper, what material is replaced by recycled fibres, how the pulpwood savings are used, what external energy carrier is used for the recycling process, and what environmental burdens are associated with a change in the electricity demand. These factors can be investigated for different decision contexts and from different ethical, time and geographical perspectives. Different choices are appropriate for different decisions and perspectives. Hence, to obtain an adequate conclusion, the comparison needs to be specified in terms of what perspectives are relevant.

Study Included	Classification	Short Summary (taken directly from the studies)
S6. Ekvall, T. 2000. A market-based approach to allocation at open-loop recycling. *Resources, Conservation and Recycling* 29(1):91-109.	1. General	This paper presents a model that takes the market aspects in consideration for open-loop recycling. The model is illustrated with two pulp and paper case studies.
S7. International Organization for Standardization (ISO). 2000. *Environmental management — Life cycle assessment — Examples of application of ISO 14041 to goal and scope definition and inventory analysis*. ISO/TR 14049. Geneva: International Organization for Standardization.	1. General	This technical report gives examples of applying ISO recommendations for LCI. An example of an allocation procedure for paper recycling is presented.
S8. Mellor, W., Wright, E., Clift, R., Azapagic, A. and Stevens, G. 2002. A mathematical model and decision-support framework for material recovery, recycling and cascaded use. *Chemical Engineering Science* 57(22-23):4697-4713. S9. Hart, A., Clift, R., Riddlestone, S. and Buntin, J. 2005. Use of life cycle assessment to develop industrial ecologies—A case study: Graphics paper. *Process Safety and Environmental Protection* 83(4B):359-363.	1/3Aa/bii	The first paper presents a new methodology—CHAin Management of Materials and Products (CHAMP)—developed for modelling the flow of materials through a succession of uses with different performance requirements. The second paper applies the methodology in combination with LCA to graphic paper in London. Analysis of the fibre flows around the supply system for paper recovery and recycling shows that, given the present low proportion of recycled fibre graphics paper used in the UK, other sources of fibre are not needed to maintain the supply and quality of the recycled material. LCA of the recycling system shows that recycling does give environmental benefits. LCA also enables possible changes in the system for recovering and reprocessing paper to be examined.
S10. Nyland, C.A., Modahl, I.S., Raadal, H.L. and Hanssen, O.J. 2003. Application of LCA as a decision-making tool for waste management systems—Material flow modelling. *International Journal of Life Cycle Assessment* 8(6):331-336.	1A/Baii	This paper analyses various material flows in a life cycle perspective. When the purpose of the study is to compare different waste management options, it is important that the system boundaries are expanded in order to include several recycling loops where this is a physical reality.
2. LITERATURE REVIEWS		
S11. Björklund, A. and Finnveden, G. 2005. Recycling revisited—Life cycle comparisons of global warming impact and total energy use of waste management strategies. *Resources, Conservation and Recycling* 44(4):309-317.	2Aai	Publications comparing the global warming impact and total energy use of recycling versus incineration and landfilling were reviewed in order to find out the extent to which they agree or contradict each other, and whether there are generally applicable conclusions to be drawn when certain key factors are considered. Producing materials from recycled resources is often, but not always, less energy-intensive and causes less global warming impact than from virgin resources. For non-renewable materials the savings are of such a magnitude that apparently the only really crucial factor is what material is replaced. For paper products, however, the savings of recycling are much smaller. The ranking between recycling and incineration of paper is sensitive to, for instance, paper quality, energy source avoided by incineration, and energy source at the mill.

Study Included	Classification	Short Summary (taken directly from the studies)
S12. European Environment Agency (EEA). 2006. *Paper and cardboard — recovery or disposal?* EEA Technical Report No 5/2006. Copenhagen: EEA. S13. Villanueva, A. and Wenzel, H. 2007. Paper waste—Recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management* 27(8):S29-S46. S14. Wenzel, H. and Villanueva, A. 2006. The significance of boundary conditions and assumptions in the environmental life cycle assessment of paper and cardboard waste management strategies. An analytical review of existing studies. In *NorLCA 2006 Symposium*. Lund, Sweden: Nordic Life Cycle Association.	2/1Aai	These studies review existing environmental and economic studies covering alternative recovery and disposal options for waste paper and cardboard. The main objective was to identify and evaluate system parameters and boundary assumptions that have been most decisive for the conclusions. They conclude that the majority of LCAs indicate that recycling of paper has lower environmental impacts than landfill incineration.
S15. Grieg-Gran, M. 1995. LCAs of paper product—What can they tell us about the sustainability of recycling. In *Life-Cycle Analysis—A Challenge for Forestry and Forest Industry* (Proceedings of the International Workshop organized by the European Forest Institute and the Federal Research Centre for Forestry and Forest Products, EFI Proceedings No. 8), ed. A. Frühwald, B. Solberg, 123-134. Hamburg, Germany.	2Aai	This paper evaluates the extent to which LCA can be useful in comparing the sustainability of waste paper recycling and burning with energy recovery.
3. CASE STUDIES		
S16. Arena, U., Mastellone, M.L., Perugini, F. and Clift, R. 2004. Environmental assessment of paper waste management options by means of LCA methodology. *Industrial and Engineering Chemistry Research* 43(18):5702-5714.	3Aai	In this study, LCA is used to assess and compare the environmental performances of three alternative options for managing paper and board packaging wastes in Italy (landfilling, recycling, and combustion with energy recovery). It is shown that using paper wastes as biofuel is a more effective option than recycling.
S17. Axel Springer Verlag AG, Stora, and Canfor. 1998. *LCA graphic paper and print products (Part 2): Report on industrial process assessment*. Axel Springer Verlag AG, Stora, Canfor. S18. Axel Springer Verlag AG, Stora and Canfor. 1998. *LCA graphic paper and print products (Part 1): Proposal for a new forestry assessment method in LCA*. Axel Springer Verlag AG, Stora Canfor	3Bbii 3/1Bbii	This study evaluates the life cycle environmental impacts of a typical newspaper and magazine along the paper cycle. It attempts to provide information and criteria for ecological optimization along the paper cycle including waste management practices. Also, a new method for evaluating the land use impacts of forest operations is proposed and applied to different types of pulp.
S19. Boguski, T. 2010. Life cycle carbon footprint of the *National Geographic* magazine. *International Journal of Life Cycle Assessment* 15(7):635-643.	3Bbii	The purpose of this study is to document the life cycle carbon footprint of the *National Geographic* magazine. The results indicate that opportunities for improving the carbon footprint of the magazine are more likely to be found within the manufacturing and printing of the paper. Including recycled fibre into magazine paper did not improve the carbon footprint of the magazine.

Study Included	Classification	Short Summary (taken directly from the studies)
S20. Byström, S. and Lönnstedt, L. 1997. Paper recycling: Environmental and economic impact. *Resources, Conservation and Recycling* 21(2):109-127.	3Aa/bi	This paper uses a combined optimization and simulation model, calculates the optimal combination of energy recovery and recycling of waste paper for paper and board production. Given a "forced" utilization rate for the Scandinavian forest industry, optimization of marginal revenue shows environmental impact to be at a minimum with a utilization rate of about 30% in Scandinavia and 73% (an assumed upper limit) for the rest of Europe. If instead environmental impact is minimized, the utilization rate for Scandinavia is almost the same, while the utilization rate for the rest of Europe is 53%. Given a fixed use of virgin fibres for the rest of Western Europe, a comparison of the environmental load at different "forced" utilization rates for the Scandinavian forest industry shows no significant differences between the economic and environmental optimizations.
S21. Dahlbo, H., Laukka, J., Myllymaa, T., Koskela, S., Tenhunen, J., Seppälä, J., Jouttijärvi, T. and Melanen, M. 2005. *Waste management options for discarded newspaper in the Helsinki Metropolitan Area—Life cycle assessment report*. FE752. Helsinki: Finnish Environment Institute. S22. Dahlbo, H., Ollikainen, M., Peltola, S., Myllymaa, T. and Melanen, M. 2005. *Combining ecological and economic assessment of waste management options—Case of newspaper*. Discussion Paper no. 9. Helsinki: University of Helsinki, Department of Economics and Management.	3Aaii	In this project, the ecological and economic sustainability of waste management is assessed by performing an LCA study on newspaper in Helsinki with particular attention to waste management practices. Five waste management options for newspaper waste (including material and energy recovery and landfilling) are studied.
S23. Dias, A.C., Arroja, L. and Capela, I. 2007. Life cycle assessment of printing and writing paper produced in Portugal. *International Journal of Life Cycle Assessment* 12(7):521-528.	3Aaii	The main goal of the paper is to assess the potential environmental impacts associated with the entire life cycle of the printing and writing paper produced in Portugal. A secondary objective is to evaluate the effect on the potential environmental impacts of changing the market where the Portuguese printing and writing paper is consumed: German market vs. Portuguese market, and hence the end-of-life conditions. The results show that for some parameters/impact categories, the German market has a better performance because recycling dominates in Germany, whereas landfilling dominates in Portugal.
S24. Edwards, C. and Meyhoff Fry, J. 2011. *Life cycle assessment of supermarket carrier bags*. SC030148. Bristol, UK: Environment Agency.	3Aaii	This objective of this study, commissioned by the Environment Agency, was to assess the life cycle environmental impacts of the production, use and disposal of different carrier bags, including paper bags, for the UK. The effect of increasing recycling at the end-of-life was also studied.

Study Included	Classification	Short Summary (taken directly from the studies)
S25. Environmental Resources Management (ERM). 2007. *Life cycle assessment of tissue products*. Report prepared for Kimberly-Clark. Environmental Resources Management.	3Bbii	The goal of this study is to determine the environmental performance of tissue products manufactured by Kimberly-Clark and the environmental trade-offs associated with the use of virgin fibres and recycled fibres in tissue products. The results indicate that neither fibre type can be considered environmentally preferable.
S26. Finnveden, G., Johansson, J., Lind, P. and Moberg, Å. 2005. Life cycle assessment of energy from solid waste—Part 1: General methodology and results. *Journal of Cleaner Production* 13(3):213-229. S27. Moberg, Å., Finnveden, G., Johansson, J. and Lind, P. 2005. Life cycle assessment of energy from solid waste—Part 2: Landfilling compared to other treatment methods. *Journal of Cleaner Production* 13(3):231-240. S28. Finnveden, G., Johansson, J., Lind, P. and Moberg, Å. 2000. *Life cycle assessment of energy from solid waste*. FOA-B--00-00622-222-SE fms 137. Stokholm: Stockholms Universitet/Systemekologi and FOA, Forskningsgruppen för Miljöstrategiska Studier.	3Aai	The objective of this study is to evaluate different strategies for treatment of solid waste in Sweden based on a life cycle perspective. A waste hierarchy suggesting the environmental preference of recycling over incineration over landfilling is often put forward. The study indicates that the waste hierarchy is valid as a rule of thumb. However, if the waste can replace oil or coal as energy sources, and neither biofuels nor natural gas are alternatives, a policy promoting incineration of paper materials may be successful in reducing emissions of greenhouse gases. The study also concludes that assumptions made including value choices with ethical aspects are of importance when ranking waste treatment options.
S29. Gaudreault, C., Samson, R. and Stuart, P. 2009. Implications of choices and interpretation in LCA for multi-criteria process design: deinked pulp capacity and cogeneration at a paper mill case study. *Journal of Cleaner Production* 17(17):1535-1546. S30. Gaudreault, C., Samson, R. and Stuart, P.R. 2010. Energy decision making in a pulp and paper mill: selection of LCA system boundary. *International Journal of Life Cycle Assessment* 15(2):198-211.	3/1Bbii	These papers demonstrate the importance of methodological choices in LCA when used for process design. This is demonstrated using a case study involving the implementation of deinked pulp capacity and cogeneration and an integrated newsprint mill.
S31. Gaudreault, C., Wising, U., Martin, G., Samson, R. and Stuart, P.R. 2008/2009. Environmental benchmarking of energy-related kraft mill modifications using LCA. *Pulp and Paper Canada* 109/12(12/1):23-30.	3Bbii	This paper uses LCA to evaluate different process options at a kraft pulp and paper mill, including an increase in deinked pulp consumption.
S32. Grant, T., James, K.L., Lundie, S. and Sonneveld, K. 2001. *Stage 2 report for life cycle assessment for paper and packaging waste management scenarios in Victoria*. Victoria, Australia: EcoRecycle.	3Aai	The objective of this study is to provide a model for the management of paper and packaging wastes in Victoria, Australia. It concludes that for the indicator evaluated, recycling provides substantial benefits.
S33. Joint Research Center. 2007. *Environmental assessment of municipal waste management scenarios: Part I - Data collection and preliminary assessments for life cycle thinking pilot studies*. EUR 23021EN. Luxembourg: European Commission Joint Research Centre.	3Aai	This report presents the research study results of life cycle assessments for municipal waste management in two Polish regions. Several scenarios involving a combination of incineration or composting with recycling are analyzed and show environmental benefits. Scenarios with higher recycling rates showed better results.

Study Included	Classification	Short Summary (taken directly from the studies)
S34. Laurijssen, J., Marsidi, M., Westenbroek, A., Worrell, E. and Faaij, A. 2010. Paper and biomass for energy?: The impact of paper recycling on energy and CO_2 emissions. *Resources, Conservation and Recycling* 54(12):1208-1218.	3Aa/bii	In this study, the energy use and carbon dioxide emissions for paper production from three pulp types are calculated. Increased recycling enables an increase in biomass availability and reduces life-cycle energy use and carbon dioxide emissions. Large differences exist between paper grades. However, in all paper grades, life-cycle energy use decreases with increased recycling rates and increased use of recovered fibres.
S35. Merrild, H., Damgaard, A. and Christensen, T.H. 2008. Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. *Resources, Conservation and Recycling* 52(12):1391-1398.	3Aai	This paper evaluates the significance of data and system boundary choices, when modelling the environmental impact from recycling and incineration of waste paper using LCA. It concludes that for recycling, the choice of virgin paper manufacturing data is the most important parameter for the result, but that the impacts from the reprocessing technologies also fluctuate greatly. Their models also show that recycling of paper is environmentally equal to or better than incineration with energy recovery only when the recycling technology is at a high level of environmental performance and that expanding the system to include substitution of fossil fuel energy by production of energy from the biomass that would have otherwise been used to produce virgin fibre will give a completely different result.
S36. Mourad, A.L., Garcia, E.E.C., Vilela, G.B. and Von Zuben, F. 2008. Influence of recycling rate increase of aseptic carton for long-life milk on GWP reduction. *Resources, Conservation and Recycling* 52(4):678-689.	3Baii	The objective of this paper is to analyze the life cycle global warming potential associated with the increase in recycling rate (from 2% up to 22%) of the cardboard contained in the aseptic packaging for long-life milk. The study concludes that the increase in the recycling rate brings a series of environmental benefits.
S37. Pickin, J.G., Yuen, S.T.S. and Hennings, H. 2002. Waste management options to reduce greenhouse gas emissions from paper in Australia. *Atmospheric Environment* 36(4):741-752.	3Aaii	The objective of this study is to provide a comprehensive investigation of total GHGs from the paper cycle in Australia and to assess the effectiveness of various waste management options to reduce GHGs from paper. Options that keep paper out of landfills significantly reduce greenhouse emissions, waste-to-energy recovery being most effective. Recycling is also beneficial, and is of particular interest from a management perspective because it can be controlled by the pulp and paper industry.

Study Included	Classification	Short Summary (taken directly from the studies)
S38. Ryberg, A., Ekvall, T. and Person, L. 2000. *Life Cycle Assessment of distribution in four different distribution systems in Europe*. Stockholm: CIT Ecologik, Chalmers Industriteknik.	3Aaii	The primary purpose of this study is to compare the environmental impacts of distribution of paper sacks with the environmental impacts of distribution of other systems for filling goods in Europe. Four scenarios concerning the after use phase are included for the paper sack system: 100% recycling, 100% incineration, 100% landfilling and 100% composting. The landfill scenario gives the highest contribution to global warming, due to the formation of methane when the paper is degraded in landfill.
S39. Schmidt, J.H., Holm, P., Merrild, A. and Christensen, P. 2007. Life cycle assessment of the waste hierarchy - A Danish case study on waste paper. *Waste Management* 27(11):1519-1530.	3Aa/bii	The waste hierarchy is being widely discussed not only by cost-benefit analysts; a growing number of LCAs have also begun to question it. In this article, the handling of waste paper in Denmark is investigated and based on consequential LCA. The results indicate that the waste hierarchy is reliable; from an environmental point of view, recycling of paper is better than incineration and landfilling. For incineration, the advantage over landfilling mainly comes from the substitution of fossil fuels, when incinerators provide heat and electricity. For recycling, the advantage is related to the saved wood resources, which can be used for generating energy, i.e., from renewable fuel which does not contribute to global warming.
S40. Tiedemann, A. 2001. *Life cycle assessments for graphic papers*. Nr 2/2001, Umweltbundesamt. Berlin: German Federal Environmental Agency.	3Aa/bii	The objectives of this study are to rank the recycling and disposal options for German graphic papers and to compare waste paper with wood as a fibre source. It concludes that recycling is better than burning (except if coal power is displaced), that it is better than landfilling, and that 100% recycled paper is considerably preferable to 100% virgin.
S41. United States Environmental Protection Agency (USEPA). 2006. *Solid waste management and greenhouse gases – A life cycle assessment of emissions and sinks,* 3rd ed. EPA530-R-06-004. Washington, DC: United States Environmental Protection Agency.	3Aai	This report examines the interrelationship between municipal solid waste management and GHG emissions using a life cycle approach. It concludes that source reduction and recycling can reduce GHG emissions at the manufacturing stage, increase forest carbon sequestration, and avoid landfill CH_4 emissions.

A.2 LIST OF DOCUMENTS CONSIDERED BUT EXCLUDED

Note: Generic LCA studies on waste management were not considered if paper was not mentioned in the abstract.

Study Excluded	**Classification**	**Short Summary** **(taken directly from the studies)**	**Reason for Exclusion**
1. METHODOLOGICAL PAPERS			
S42. Bjarnadóttir, H.J., Friðriksson, G., Johnsen, T. and Sletsen, H. 2002. Guidelines for the use of LCA in the waste management sector. TR 517. Espoo, Finland: Nordtest.	1/2Aai	This report contains guidelines for the application of LCA in the waste management sector. Focus is put on the most common municipal waste management scenarios in the Nordic countries. Pulp and paper examples are given.	Not specific to paper.
S43. Clift, R., Doig, A. and Finnveden, G. 2000. The application of life cycle assessment to integrated solid waste management: Part 1—Methodology. *Process Safety and Environmental Protection* 78(B4):279-287.	1Aai	This paper summarizes a methodology for applying LCA to integrated waste management of municipal solid waste (MSW) developed for and now used by the UK Environment Agency, including recent developments in international fora. Particular attention is devoted to system definition leading to rational and clear compilation of the Life Cycle Inventory, with appropriate "credit" for recovering materials and/or energy from the waste. LCA of waste management is best seen as a way of structuring information to help decision processes.	Not specific to paper.
S44. Ekvall, T. 1999b. *System expansion and allocation in life cycle assessment - with implications for wastepaper management*. Dissertation, Chalmers University of Technology, Göteborg, Sweden.	1A/Bai	This thesis discusses system expansion in the context of wastepaper.	Several papers from that thesis included.
S45. Ekvall, T., Assefa, G., Björklund, A., Eriksson, O. and Finnveden, G. 2007. What life-cycle assessment does and does not do in assessments of waste management. *Waste Management* 27(8):989-996. S46. Finnveden, G. 1999. Methodological aspects of life cycle assessment of integrated solid waste management systems. *Resources, Conservation and Recycling* 26(3-4):173-187.	1Aai	The applicability of LCA for waste management planning and policy-making is restricted by certain limitations, some of which are characteristics inherent to LCA methodology as such, and some of which are relevant specifically in the context of waste management. These papers list such characteristics and evaluate them with regard to how they may restrict the applicability of LCA in the context of waste management. Efforts to improve LCA with regard to these aspects are also described.	Not specific to paper.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S47. Ekvall, T., Rydberg, T., Hedenberg, Ö., Backlund Jacobson, B., Pajula, T. and Wessman, H. 1997. *Guidelines on life cycle impact assessment of pulp and paper*. Nordpap DP2/55. SCAN Forskrapport, 688. CIT Ekologik, Chalmers Industriteknik, Gothenburg, Sweden.	1A/Ba/bii	This report proposes guidelines for LCI of forest products.	Not easily available.
2. LITERATURE REVIEW			
S48. Denison, R.A. 1996. Environmental life cycle comparisons of recycling, landfilling, and incineration: A Review of recent studies. Annual Review of Environment and Resources 21:191-237.	2Aai	This paper reviews and analyzes the major recent North American studies that have compared, on an environmental basis, the major options used to manage the materials that comprise municipal solid waste (MSW). The review finds that all of the studies support the following conclusion: Systems based on recycled production plus recycling offer substantial system-wide or "life-cycle" environmental advantages over systems based on virgin production plus either incineration or landfilling.	Not specific to paper. Too old.
S49. Cleary, J. 2009. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International* 35(8):1256-1266.	2Aai	This paper is a comparative analysis of 20 LCAs of municipal solid wastes published between 2002 and 2008. It quantifies the methodological transparency of the studies and the frequency of use of particular system boundaries, types of data sources, environmental impact categories, impact weightings, economic valuations, sensitivity analyses, and LCA computer models. The reviewed LCAs differ substantially in their system boundaries. All but one of these concurred with the "hierarchy of waste" that the environmental performance of landfilling is lower than that of all the other treatment methods, and that thermal treatments are inferior to recycling.	Not specific to paper.
S50. Ekvall, T. (1992). *Life cycle analyses of corrugated cardboard: A comparative analysis of two existing studies*. CIT Ekologik Report 1992:3. Gothenburg, Sweden: Chalmers Industriteknik,.	2A/B. No info on objective. Ii	N/Av.	Too old. Not easily available.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S51. Finnveden, G. and Ekvall, T. 1998. Life-cycle assessment as a decision-support tool—The case of recycling versus incineration of paper. *Resources, Conservation and Recycling* 24(3-4):235-256.	2/1Aai	LCAs on recycling and incineration with energy recovery of paper packaging materials are used as examples in order to discuss the usefulness of LCAs. The reproducibility of LCAs is evaluated and reasons for possible discrepancies between LCAs are discussed. An attempt is also made to make conclusions on advantages to the environment of recycling versus incineration of paper packaging materials. In all studies, total energy use is consistently lower when paper packaging materials are recycled rather than incinerated. Dffering results can be explained by the assumptions made concerning the energy source used instead of the energy from incineration when paper is recycled instead of incinerated. If fossil fuels are the alternative energy source, incinerated paper replaces fossil fuels, and emissions of CO_2 can be decreased. If, on the other hand, solid waste (which in other cases would have been landfilled) or biofuels are the alternative energy source, fossil fuels will not be replaced. In these cases, increased recycling will in general lead to decreased emissions of GHGs. Studies which address the issue of transportation consistently conclude that as long as it is reasonably efficient, transport will have no effect on the conclusions. Not all relevant environmental impacts are considered in the reviewed studies. It is concluded that LCAs cannot be used alone be determine the environmental preference of the alternatives studied.	All reviewed studies are too old.
S52. Kirkpatrick, N. 2004. *A review of LCA studies commissioned by EUROPEN*. Brussels: European Organization for Packaging and the Environment.	2Aai	This report assesses the usefulness of LCA for recycling questions.	Not specific to paper. Not enough background information.
S53. Powell, J. C., Pearce, D., and Howarth, A. 1999. *Burn or return? A review of the life cycle assessments of waste newspaper management*. On commission of British Newsprint Manufacturers' Association. Economics for the Environment Consultancy Ltd (EFTEC) and Centre for Social and Economic Research on the Global Environment (CSERGE), United Kingdom.	2Aai	N/Av.	Not easily available.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S54. Dahlbo, H., Jouttijärvi, T., Koskela, S., and Melanen, M. 2002. *Waste management systems of paper products in life cycle assessment. Literature survey*. Finnish Environment Institute Mimeograph 261. Helsinki: Finnish Environment Institute. Original title: Paperituotteiden jätehuoltojärjestelmät elinkaaritutkimuksissa. Kirjallisuuskatsaus.	2Aai	This publication provides an overview of the LCA-WASTE project[7] as well as an overview of the research concerning waste management of paper and more specifically, life cycle studies comparing different waste management alternatives.	In Finnish. Several other publications on the same project were retained for analysis.
S55. Danish EPA. 2005. *Environmental issues from recycling paper and cardboard – Updating the knowledge base.* Environmental Project 1057. Original title : Miljømæssige forhold ved genanvendelse af papir og pap - Opdatering af vidensgrundlaget.	2Aai	The project objective was to provide a basis for assessing whether, in Denmark, under specific conditions, recycling or incineration of waste paper should be promoted because of environmental benefits.	In Danish.
3. CASE STUDIES			
S56. Axel Springer Verlag AG, Stora, and Canfor. 1998. *A life cycle assessment of the production of a daily newspaper and a weekly magazine* (Short version of the study).	3/1Baii	This study evaluates the life cycle environmental impacts of a typical newspaper and magazine along the paper cycle. It attempts to provide information and criteria for ecological optimization along the paper cycle including waste management practices.	Original full report included.
S57. Baumann, H., Ekvall, T., Eriksson, E., Kullman, M., Rydberg, T., Ryding, S-O., Steen, B., Svensson, G. 1993. Environmental differences between recycling/reuse and incineration/landfill (unofficial translation), FoU nr 79 (in Swedish). Malmo, Sweden: Stiftelsen Reforsk. Original title: Miljömässiga skillnader mellan återvinning/återanvandning och förbränning/deponering	3Aai	N/Av.	Too old. In Swedish.
S58. Björklund, A.E. and Finnveden, G. 2007. Life cycle assessment of a national policy proposal - The case of a Swedish waste incineration tax. *Waste Management* 27(8):1046-1058.	3Aia	This paper presents the results of a LCA of a waste incineration tax proposal. The proposed design of the waste incineration tax results in increased recycling, but only in small environmental improvements.	Not specific to paper.

[7] In the LCA-WASTE project, an LCA study was performed for waste management options of newspaper in the Helsinki region. The economic and environmental impacts of waste management options were assessed. Integrated analysis of municipal solid waste management will be combined with the LCA of a product (see http://www.ymparisto.fi/default.asp?node=11104&lan=en#a0).

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S59. Craighill, A., and Powell, J.C. 1995. *Life cycle assessment and economic evaluation of recycling: A case study*. CSERGE Working Paper WM 95-05. Centre for Social and Economic Research on the Global Environment University of East Anglia and University College London. S60. Craighill, A. and Powell, J. 1996. Lifecycle assessment and economic evaluation of recycling: A case study. *Resources, Conservation and Recycling* 17(2):75-96.	3Aia	This study compared the relative environmental impacts of a recycling system with a waste disposal system using LCA and extended the methodology to incorporate an economic evaluation of the environmental impacts. The study concludes that recycling is better in environmental terms than waste disposal to landfill for aluminum, glass, and paper.	Too old.
S61. Counsell, T.A.M. and Allwood, J.M. 2007. Reducing climate change gas emissions by cutting out stages in the life cycle of office paper. *Resources, Conservation and Recycling* 49(4):340-352.	3Biia/b	This article evaluates options to reduce emissions from cut-size office paper: incineration, localisation, annual fibre usage, fibre recycling, un-printing[8], and electronic-paper. It is concluded that un-printing may offer the greatest greenhouse gas emission reduction.	Not consistent with the ISO standard.
S62. Daae, E. and Clift, R. 19XX. A Life Cycle Assessment of the Implications of Paper Use and Recycling. University of Surrey Environmental Protection Bulletin 028, pp. 1-3.	3Aia	LCA is used to compare incineration and recycling of waste newsprint. It concludes that it should be burned as a biofuel rather than recycled.	Not enough background information. Probably too old.
S63. Dahlbo, H. 2006. Combining ecological and economic assessments of waste management. Presented at PEER Environmental Technology Seminar "TOWARD SUSTAINABLE PRODUCTION AND CONSUMPTION - Needs, methods and opportunities for research. Montpellier, France. October 11-12, 2006.	3Aia	An LCA and an economic analysis of social life cycle costs were combined to investigate five alternatives for newspaper waste management.	Full report already retained for analysis.

[8] Reversing the effects of printing without damaging the underlying sheet.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S64. Dahlbo, H., Ollikainen, M., Peltola, S., Myllymaa, T. and Melanen, M. 2006. Newspaper waste management–A combined assessment of ecological and economic aspects. In *NorLCA 2006 Symposium*. Lund, Sweden: Nordic Life Cycle Association. S65. Dahlbo, H., Ollikainen, M., Peltola, S., Myllymaa, T. and Melanen, M. 2007. Combining ecological and economic assessment of options for newspaper waste management. *Resources, Conservation and Recycling* 51(1):42-63. Dahlbo, H., Myllymaa, T., Laukka, J., Koskela, S., Jouttijärvi, T. and Melanen, M. 2003. LCIs for newspaper with different waste management options - Case Helsinki Metropolitan Area. In *Proceedings of Advances in Waste Management and Recycling Symposium*. University of Dundee, Scotland. S66. Dahlbo, H. 2003. Recycling, incineration or landfill–Preliminary results of the LCA-WASTE project. Presented at 17th National Waste Management Seminar, 1-2 October 2003, Tampere, Finland. Original title: Sanomalehtipaperin jätehuoltovaihtoehdot: Kierrätys, poltto vai kaatopaikka - LCA-WASTE-hankkeen alustavia tuloksia. S67. Laukka J. 2003. Life cycle inventories of newspaper with different waste management options. A case study in the Helsinki Metropolitan Area. M.Sc. thesis, University of Kuopio.	3Aai/ii	This series of papers presents the background and results for the LCA-WASTE project. In this project, the ecological and economic sustainability of waste management is assessed by performing an LCA study on newspaper in Helsinki with particular attention to waste management practices. Five waste management options for newspaper waste (including material and energy recovery and landfilling) are studied.	Reasons for excluding these papers: 1) not enough background information, 2) language, 3) inclusion of LCI results only, 4) not easily available. Several other publications on the same project were retained for analysis.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S68. Dahlbo, H., Tenhunen, J., Seppälä, J., Myllymaa, T., Koskela, S., Jouttijärvi, T., Peltola, S., Ollikainen, M. and Melanen, M. 2004. Recycle, burn or landfill–Impacts of the life cycle of newspaper with different waste management options. Presented at the Integrated Waste Management & Life Cycle Assessment Workshop & Conference. Prague. S69. Dahlbo, H., Ollikainen, M., Peltola, S. & Myllymaa, T. 2005. Combining ecological and economic assessment of waste management options–The case of newspaper. In *Waste management in the focus of controversial interests*. Proceedings of the 1st BOKU Waste Conference, ed. P. Lechner, 355-361. Vienna, ABF-BOKU. S70. Dahlbo, H., Koskela, S., Laukka, J., Myllymaa, T., Jouttijarvi, T., Melanen, M. and Tenhunen, J. 2005. Life cycle inventory analyses for five waste management options for discarded newspaper. *Waste Management and Research* 23(4):291-303. S71. Tanskanen, J.-H., and Dahlbo, H. 2001. Life cycle approach to sustainable waste management—A case study on newspaper (LCA-WASTE). In *Sustainable development—The challenges and possibilities of research*. GTK-SYKE research seminar 12.9.2001. Original title: Elinkaarinäkökulma kestävään jätehuoltoon - tapaustarkasteluna sanomalehti (LCA-WASTE)	3Aai	This series of papers presents the background and results for the LCA-WASTE project. In this project, the ecological and economic sustainability of waste management is assessed by performing an LCA study on newspaper in Helsinki with particular attention to waste management practices. Five waste management options for newspaper waste (including material and energy recovery and landfilling) are studied.	Reasons for excluding these papers: 1) not enough background information, 2) language, 3) inclusion of LCI results only, 4) not easily available. Several other publications on the same project were retained for analysis.
S72. Danish EPA. 1995. *Environmental economics of paper and cardboard circulation*. Environmental Project 294. Original title: Miljøøkonomi for papir- og papkredsløb.	3Aai	The purpose of this report was to use an environmental and economic analysis to assess whether it is appropriate for Denmark to increase recycling of paper and paperboard and thereby reduce the need for incineration and landfill.	Too old and in Danish.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S73. Ecobalance UK. 1998. *Newsprint–A life cycle study*. Commissioned by Aylesford Newsprint.	3Baii	An LCA approach is used to investigate environmental inputs and outputs and associated environmental impacts of the alternative options for the disposal of newspapers and magazines (recycling into newsprint and incineration). The study concludes that recycling of used newspapers and magazines at ANL is environmentally preferable to their incineration for energy recovery.	Full report not available. The summary has no indication that the study has been peer-reviewed.
S74. Ecolas and Pira. 2005. *Study on the Implementation of Directive 94/62/EC on Packaging and Packaging Waste and Options to Strengthen Prevention and Re-Use of Packaging*. Report 03/07884/AL. Ecolas-Pira.	3/2Aai	This study evaluates the implementation of a directive for reduction and reuse of packaging material in Europe. As part of this evaluation an LCA has been performed. It concludes that, for the case of corrugated board, results are very dependent on modelling choices.	Not enough background information. Very simplified.
S75. Environmental Defense Fund. 2002. *Lifecycle environmental comparison: Virgin paper and recycled paper-based systems*. New York: Paper Task Force.	3Aa/bi/ii	This paper summarizes the research and findings of the Paper Task Force on the environmental impacts associated with paper recycling in comparison with managing paper through the major means of solid waste management. Landfilling, incineration (with energy recovery) and recycling are compared using the following three alternative complete "systems": (1) acquisition of virgin fibre, manufacture of virgin paper, followed by landfilling; (2) acquisition of virgin fibre, manufacture of virgin paper, followed by incineration; and (3) manufacture of recycled paper, followed by recycling collection, processing and transport to the site of remanufacture. The paper has the following conclusion: With the exception of solid wastes and fossil-fuel energy, the recycling option generally has a better environmental performance than the two virgin production options.	Not consistent with the ISO standard.
S76. Eriksson, O., Carlsson Reich, M., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A. and Thyselius, L. 2005. Municipal solid waste management from a systems perspective. *Journal of Cleaner Production* 13(3):241-252. S77. Eriksson, O., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.-O., Granath, J., Carlsson Reich, M., Baky, A. and Thyselius, L. 2001. Energy recovery and material and nutrient recycling from a systems perspective. In *Workshop on System Studies of Integrated Solid Waste Management*, 40-54. Stockholm: IVL.	3Aia	Different waste treatment options for municipal solid waste are studied in a systems analysis (use of energy resources, environmental impact and financial and environmental costs). The study shows that reduced landfilling in favour of increased recycling of energy and materials leads to lower environmental impact, lower consumption of energy resources, and lower economic costs.	Not specific to paper.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S78. Finnveden, G., Steen, B., and Sundqvist, J.-O. 1994. *Circulation of paper packaging: Material recycling or energy recovery? An environmental study based on five real cases*. IVL Report No B1128. Stockholm: Swedish Environmental Research Institute. Original title: Kretslopp. av pappersförpackningar: materialåtervinning eller energiåtervinning? En miljöstudie baserad på fem verkliga fall.	3Aai	N/Av.	Too old. In Swedish.
S79. Finnveden, G., Person, L. and Steen, B., 1994. *The recycling of milk cartons. An LCA study of differences in environmental load* (unofficial translation). Rapport 4301 (in Swedish). Stockholm: Swedish Environmental Protection Agency. Original title: Återvinning av mjölkkartong. En LCA-studie av skillnader i miljö belastning. Bilaga 2 till Förpackningar i kretsloppet.	3Aai	N/Av.	Too old. In Swedish.
S80. Gaudreault, C., Samson, R. and Stuart, P.R. 2009. Using LCA to enhance EMS: Pulp and paper case study. *Environmental Progress & Sustainable Energy* 28(4):576-588.	3Bbii	This article proposes a methodology for the integration of LCA into environmental management systems. It uses a pulp and paper case study, which includes the increase of deinked pulp consumption, to demonstrate the proposed methodology.	Case study already included in other publications.
S81. Granath, G., and Strömdahl, I. 1994. *Estimates of the environmental impact of recycling bill. Life cycle analysis of packaging* (unofficial translation). Rapport 4300 (in Swedish). Stockholm: Swedish Environmental Protection Agency. Original title: Beräkningar av miljökonsekvenser av kretsloppspropositionen. Livscykelanalys av förpackningar. Bilaga 1 till Förpackningar i kretsloppet.	3Aai	N/Av.	Too old. In Swedish.
S82. Grant, T., James, K.L. and Partl, H. 2003. L*ife cycle assessment of waste and resource recovery options (including energy from waste)*. Victoria, Australia: EcoRecycle.	3Aai	The goal of this LCA is to provide a transparent environmental evaluation of a range of waste management technologies for dealing with mixed waste fractions and organic waste fractions of the Victorian waste stream. The study has confirmed that material recycling is a significant contributor to the environmental performance of any waste management system.	Not specific to paper.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S83. Hekkert, M.P. 2000. Improving material management to reduce greenhouse gas emissions. Ph.D. Thesis. Utrecht University	3Aa/bii	This thesis looks at different options to reduce GHG emissions for wood and paper products.	Not enough information on the background information. More conceptual.
S84. Kärnä, A., Pajula, T., Kutinlahti, T. 1994. Life cycle analysis of printing papers. In *Proceedings of the first PPI recycling conference*, London. S85. Kärnä, A., Engström, J., Kutinlahti, T. and Pajula, T. 1994. Life cycle analysis of newsprint: European scenarios. *Paperi ja Puu—Paper and Timber* 76(4): 232–237. S86. Pajula, T., and Kärnä, A. 1995. Life cycle scenarios of paper. In *Proceedings of Ecopapertech*, 191–203. Helsinki: Finnish Pulp and Paper Research Institute (KCL).	3Aiai	This study compared newspaper recycling and incineration.	Too old and not easily available.
S87. Morris, J. 2005. Comparative LCAs for curbside recycling versus either landfilling or incineration with energy recovery. *International Journal of Life Cycle Assessment* 10(4):273-284.	3Aai	In this paper, LCA is used to evaluate the environmental burdens associated with collection and management of municipal solid waste projects. Environmental burdens from curbside collection for recycling, processing, and market shipment of recyclable materials picked up from households and/or businesses are compared with environmental burdens from curbside collection and disposal of mixed solid waste. The study concludes that recycling of newspaper, cardboard and mixed paper generally results in lower environmental impacts.	Not enough background information.
S88. Mourad, A.L., Garcia, E.E.C., Vilela, G.B. and von Zuben, F. 2008. Environmental effects from a recycling rate increase of cardboard of aseptic packaging system for milk using life cycle approach. *International Journal of Life Cycle Assessment* 13(2):140-146.	3Baii	The objective of this paper is to analyze the life cycle inventory associated with the increase in recycling rate (from 2% up to 22%) of the cardboard contained in the aseptic packaging for long-life milk. The study concludes that the increase in the recycling rate brings a series of environmental benefits.	Life cycle inventory only.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S89. Økstad, E. 1995. Experience with LCA in the pulp, paper and packaging industry in Norway. In *Life-cycle analysis–A challenge for forestry and forest industry* (Proceedings of the international workshop organized by the EuropeanForest Institute and the Federal Research Centre for Forestry and Forest Products, EFI Proceedings No. 8), ed. A. Frühwald, B. Solberg, 123-134. Hamburg, Germany.	3Aai	This paper evaluates the environmental impacts of various recycling scenarios in Norway and discusses the challenges of using LCA for this purpose.	Too old.
S90. Pickin, J.G., 1996. Paper and the greenhouse effect: A life-cycle study. Honours Thesis. University of Melbourne, unpublished.	N/Av.	N/Av.	Too old and not available.
S91. Pineda-Henson, R., Culaba, A.B. and Mendoza, G.A. 2002. Evaluating environmental performance of pulp and paper manufacturing using the analytic hierarchy process and life-cycle assessment. *Journal of Industrial Ecology* 6(1):15-28.	3Bbii	In this paper, the analytic hierarchy process (AHP) is used as the basic framework for analyzing environmental impacts and improvement options following a streamlined life-cycle assessment (LCA) approach that is focused on the manufacturing operation using a pulp and paper manufacturing case study.	Background information insufficient.
S92. Rutegård, G. 1999. *Consequential analysis of using collected newspaper and journals for material recycling or energy recovery in a life cycle perspective*. Pressretur AB, Sweden. Original title: Konsekvensanalys I livscykelperspektiv av att använda insamlade tidningar och tidskrifter till materialåtervinning alternativt energiutvinning	3Aai	N/Av.	In Swedish. Not easily available.
S93. Schonert, M., Metz, G., Detzel, A., Giegrich, J., Ostermayer, A., Schorb, A., and Schmitz, S. 2001. *Ecobalance for beverage packaging II, Phase 2*. No 51/02, Umweltbundesamt, the German Federal Environmental Agency, Berlin, Germany. Original title: Ökobilanz für Getränkeverpackungen II, Phase 2.	N/Av.	This study evaluates the environmental impact of different packaging systems including waste management options.	In German.

Study Excluded	Classification	Short Summary (taken directly from the studies)	Reason for Exclusion
S94. Sharma, V.K. 2000. Wastepaper in Mumbai (India)–An approach for abridged life cycle assessment. *International Journal of Life Cycle Assessment* 5(1):12-18.	3Aai	This paper presents the results of an LCA on wastepaper management in Mumbai (India). The paper shows that while there is a moderate environmental impact of wastepaper during generation, collection and disposal stages, the utilisation stage had a significant impact on the environment, especially during manufacturing in paper factories.	Not enough background information.
S95. Tillman, A. M., Baumann, H., Eriksson, E., Rydberg, T. 1991. Life cycle analyses of selected packaging materials. Quantification and environmental loadings. Offprint from Miljön och förpackningarna, SOU, 1991:76.	3Aaii	This study characterized the environmental profile of the life cycle of different products, including corrugated board and paper board for packaging liquids and evaluated different end-of-life scenarios.	Too old and not easily available.
S96. Virtanen, Y. and Nilsson, S. 1993. *Environmental impacts of waste paper recycling*. London: Earthscan.	N/Av.	This book summarizes a study of paper recycling in Europe, which investigated the entire production and disposal process using a life-cycle methodology. The results of the study underline the economic and environmental advantages of paper recycling, and also show how, under certain conditions, the renewable character and the high energy content of paper seem to make energy recovery more attractive than recycling.	Too old.
S97. Wiegard, J. 2001. Life cycle assessment for practical use in the paper industry. *Appita Journal* 54(1):9-14. S98. Wiegard, J. 2001. Quantification of greenhouse gases at Visy Industries using life cycle assessment. Master Thesis. Melbourne Australia: Swinburne University of technology.	3Bbii	LCA is used to quantify Visy's GHG emissions across the entire life cycle of the Visy paper recycling and virgin papermaking processes. The effect of different energy sources, technologies and manufacturing processes is analyzed.	Does not meet minimum requirement for comparative assertion. No discussion of the functional equivalency of the compared systems.

APPENDIX B

DETAILED SUMMARIES

B.1 METHODOLOGICAL PAPERS

S1. LCI USER'S GUIDE

Document Information

Full reference: American Forest & Paper Association (AF&PA). 1996. *Life cycle inventory analysis user's guide - Enhanced methods and applications for the forest products industry*. Washington, DC: American Forest & Paper Association.
How to obtain: Purchase from Tappi
Paper grades: Paper and paperboard products
Classification:
- **Perspective:** General
- **Objective:** General
- **Function:** Related to the production of a paper product for a certain usage

Geography: US

Summary

Objectives: This user's guide is an attempt to enhance methods employed for life cycle inventory (LCI) with regards to forest products. It is the result of a collaborative effort of several international experts. This guide was developed in parallel with the ISO standards on LCA and its intent is to be consistent with those. No recommendations were formulated regarding impact assessment.

Recommendations: The guide provides recommendations on 1) functional unit, 2) system boundaries, 3) renewable nature of resources and final material, 4) renewable nature of the energy consumed, 5) solid waste management practices, 6) carbon sequestration, 7) allocation for co-products and recycling, and 8) interpretation of results. A more detailed summary of important recommendations was presented in Section 4.2.4.

Note

Although the guide recognized the need for updates to properly reflect the knowledge and experience gained and was published in 1996, no update is available.

S2. METHODOLOGICAL APPROACHES FOR PAPER RECYCLING

Document Information

Full reference: Byström, S. and Lönnstedt, L. 2000. Paper recycling: A discussion of methodological approaches. *Resources Conservation and Recycling* 28(1-2):55-65.
How to obtain: Purchase from www.sciencedirect.com
Paper grades: General
Classification:
- **Perspective:** Comparison of end-of-life options
- **Objective:** Management of used paper products
- **Function:** Newsprint

Geography: General

Summary

Objectives: Many paper products have the option to be based on virgin and/or recovered fibres. Recovered paper can also be incinerated, which would substitute fossil fuels and reduce CO_2 emissions. This system is complex and difficult to analyse and different methods can be used in this context. The purpose of this paper was to compare two approaches for analysing the fibre life cycle using a newsprint case study: a systems analytical approach and a life cycle analyses approach where allocation methods are used.

Methodology: As illustrated in Figure B-1, two production lines were evaluated. The first one produced newsprint from virgin fibre and partly disposed of it and its end-of-life by burning with energy recovery, and partly reused it in the second line that also produced newspaper but from 100% recovered fibre. All the newsprint produced in the second line was assumed to be sent for combustion with energy recovery. The case study looked at the effect, on a generic environmental indicator (V, P, R and B are unit process loads per unit of production), of increasing the production in the second production line while maintaining constant the total production (C) using two approaches: 1) an approach that allocates the environmental load between the two lines, and 2) a system approach that looks at the entire system (no allocation).

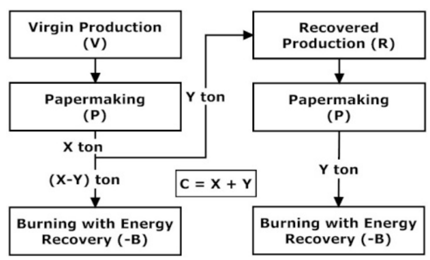

Figure B-1 Simplified Model for Open-Loop Recycling (Byström and Lönnstedt 2000

Results: When both lines were included in the boundary of the analysis (system approach), it was possible to exactly calculate the change in the generic environmental indicator and to compare the result obtained with the results obtained when applying two LCA allocation procedures (the cut-off method that considered the two production lines as two different system without interaction, and a method that splits the virgin production, recovered fibre and end-of-life loads between the two systems). It was shown that the different approaches do not necessarily lead to the same conclusions.

Conclusions: The paper concluded that the analysis of recycling and reductions in material and energy use and emissions by the pulp and paper industry is complex and often oversimplified. Hence, a system approach is necessary. If the purpose is to make a good estimation of the real effect, the allocation methods tested above cannot in general be regarded as useful methods. Decisions concerning the use of recycled materials should therefore not be based on such methods.

S3. KEY ISSUES IN THE ASSESSMENT OF WOOD FIBRE FLOWS
S4. KEY ISSUES IN THE ASSESSMENT OF PAPER RECYCLING

Document Information

Full reference:	**S3:** Ekvall, T. 1996. *Key issues in the assessment of wood fibre flows*. NORDPAP/DP2/20. Göteborg: CITekologik. **S4:** Ekvall, T. 1999. Key methodological issues for life cycle inventory analysis of paper recycling. *Journal of Cleaner Production* 7(4):281-294.
How to obtain:	**S3:** Not available **S4:** Purchase from www.sciencedirect.com
Paper grades:	Paper and paperboard products
Classification:	
Perspective:	General
Objective:	General
Function:	General
Geography:	General

Summary

The documents presented a discussion of methodological aspects (mostly LCI) important for LCAs of wood fibre related products, with an emphasis on paper recycling. The different key issues are already summarized in Section 4.2 and thus will not be repeated here.

S5. LCA AND SOLID WASTE MANAGEMENT: PAPER RECYCLING

Document Information

Full reference:	Ekvall, T. and Finnveden, G. 2000. The application of life cycle assessment to integrated solid waste management. Part 2 - Perspectives on energy and material recovery from paper. *Process Safety and Environmental Protection* 78(B4):288-294.
How to obtain:	Purchase from www.sciencedirect.com
Paper grades:	Paper and paperboard products
Classification:	
Perspective:	General
Objective:	Comparison of end-of-life management options
Function:	Management of used paper products
Geography:	Europe

Summary

Objectives: The objectives of this paper were to 1) present an overview of the important issues for the results of an LCA-based comparison between recycling and incineration with energy recovery, 2) discuss the appropriateness of specific methodological choices or assumptions for different purposes and contexts, and 3) discuss how these perspectives affect the conclusions concerning the environmental comparison between recycling and incineration with energy recovery. Perspectives were drawn from a published literature review (Finnveden and Ekvall 1998).

Main results: The key methodological issues identified for the LCA comparison of paper recycling and incineration are described next.

- *"The environmental gain of waste incineration with energy recovery depends on what energy is replaced by the energy from wastepaper.*
- *The environmental gain of recycling depends on what material is replaced by the recycled fibres.*

- *When recycled fibres replace virgin fibres as raw material for pulp production, the pulpwood requirements for this pulp production are reduced. The environmental consequences depend on how the pulpwood savings are used.*
- *When recycled fibres replace virgin fibres as raw material for pulp production, the available amount of internal, renewable fuel (bark, liquor) is reduced. The demand for external fuel is likely to increase, particularly when primary, chemical pulp is replaced. The environmental consequences depend on what external fuel is used.*
- *When pulp based on recycled fibres replaces primary, mechanical pulp, the electricity demand is reduced. The environmental gain from this reduction depends on how this electricity is produced."* (p. 289)

The paper also discussed the different perspectives from which the comparison can be made, such as decisions made from the paper user versus policy-makers, decisions based on a short-term versus long-term time horizon (for instance, over the long term, the production capacity of the different processes can change), different locations, etc.

Conclusions: The paper concluded that there is no clear-cut answer to the general question whether recycling or incineration with energy recovery is the environmentally better option for wastepaper management. The results depend on methodological choices and assumptions, and different choices are appropriate for different decisions and perspectives. To obtain an appropriate answer, the question needs to be specified very carefully in terms of what decision is at hand, what is meant by environmentally "better", and the time perspective and the geographical area.

S6. MARKET-BASED APPROACH TO ALLOCATION AT OPEN-LOOP RECYCLING

Document Information

Full reference:	Ekvall, T. 2000. A market-based approach to allocation at open-loop recycling. *Resources, Conservation and Recycling* 29(1):91-109.
How to obtain:	Purchase from www.sciencedirect.com
Paper grades:	Applicable to all paper and paperboard products, but applied to corrugated board and newsprint
Classification:	
Perspective:	General
Objective:	General
Function:	General
Geography:	General

Summary

Objectives: The objective of this paper was to propose a conceptual recycling allocation procedure that can be used to generate information on how the market would react to a change in the supply and demand of recycled material. The model was then applied to two case studies: corrugated board and newsprint.

Proposed model: The proposed model is illustrated in Figure B-2 and is based on system expansion. After its use, a product can be disposed of or collected for recycling. When it is recovered, the material from the investigated life cycle is sold in a market for this type of material (X). The market is more or less influenced by political decisions. The recovered material can be used in the same life cycle (Y) or in another one (D). If the amount of material that is collected for recycling increases in the investigated life cycle ($\Delta X>0$) and the market is sufficiently free for the recovery rate to be driven by economic forces, the price of recovered material is likely to decrease ($\Delta P<0$), which is likely to stimulate an increase use of recovered material ($\Delta Y+\Delta D>0$). However, this price reduction is also likely to make collection for recycling less profitable, which is likely to result in a reduced collection for recycling in other system ($\Delta S<0$). The global effect depends on the sensitivity of recovered material buyers and collecting organisations to variations in prices. If the investigated system increases its use of recovered material

(ΔY>0), this can reduce the availability for other systems (ΔD<0) that will need to increase their production of virgin material or increase the collection for recycling (ΔY+ΔD>0). When the flows of recovered material to and from the investigated life cycle are small compared to the market (Y<<D; X<<S), changes in the market are marginal (changes in X do not significantly affect Y and vice versa). Based on the previous assumptions and assuming the demand fulfilled by the other life cycle is constant, the indirect effects (B, effects on other life cycles) of varying X or Y can be calculated as

$$\Delta B_X \approx \frac{\Delta X}{\eta_D - \eta_S}\left[\eta_D (R_0 - AV_0) + \eta_S (C_0 - W_0)\right]$$

$$\Delta B_Y \approx \frac{\Delta Y}{\eta_S - \eta_D}\left[\eta_D (R_0 - AV_0) + \eta_S (C_0 - W_0)\right]$$

where η_D is the price elasticity of the demand, η_S the price elasticity of the supply, and A, a constant that corrects for the yield differences in virgin and recycled fibre production. Using this approach, the environmental load credited to a product delivering recovered material corresponds to the environmental load assigned to the product where the recovered material is used.

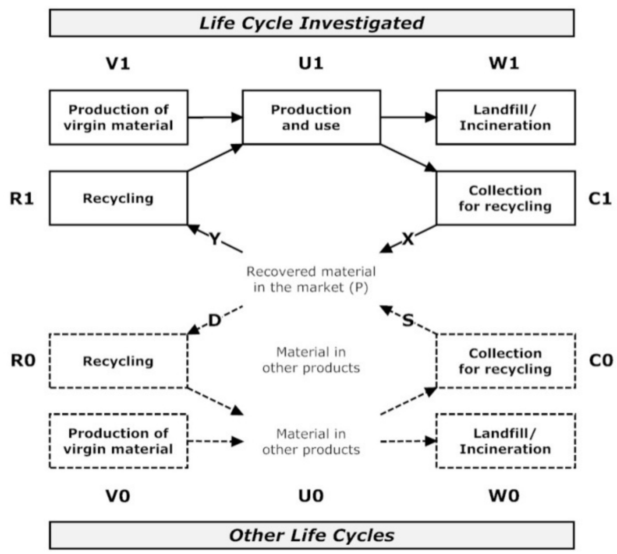

Figure B-2 Market-Based Model for Open-Loop Recycling (Ekvall 2000)

Case studies: The first case study consisted of increasing the collection rate of old corrugated containers (OCC) in Gothenburg. Using default values for price elasticities indicated that 44% of the increased flow of recovered OCC would replace virgin production and that 56% would replace OCC from other locations. The same way, it was possible to assess the effect of increasing the recovered fibre content of corrugated board in Gothenburg. The results indicated that 44% of the recovered fibre would be deviated from disposal and 56% from uses in other life cycles. Given that the default elasticities do not account for case-specific factors, these results should be considered as a best estimate with high uncertainty. The second case study consisted of increasing the collection rate of old newspapers (ONP) in Gothenburg. Since Gothenburg purchases a significant amount of imported ONP and the price of imported fibre can be significantly different from the price of local ONP, the proposed model needed to be modified to account for two different markets. This case study was used only to show that in cases of different markets with different price elasticities, the environmental load credited to a product delivering recovered material does not correspond to the load assigned to the product where the recovered material is used.

The 50/50 approximation: In cases where the price elasticities would not be known, the author recommended an assumption that 50% of an outflow of recovered material from the investigated life cycle replaces virgin material in other systems, while the other 50% replaces recovered material for other sources. To be consistent, it was necessary to also assume that an increased inflow of recovered material in the investigated system results in a 50% increase in collection for recycling and a 50% reduction in use in other life cycles.

The allocation approximation: The approach that was proposed is based on system expansion and is adequate when the objective of the study is to determine the consequences of a given action. In some cases, the objective is to describe the environmental flows to and from a specific life cycle without investigating the effect on the other affected life cycles. The model proposed above can be modified to be used as an allocation method instead but only under the following restrictions:

$V_0 \approx V_1 = V$; $R_0 \approx R_1 = R$; $W_0 \approx W_1 = W$; and $C_0 \approx C_1 = C$.

Given that the environmental load (E) of one unit of inflow or outflow of recovered material can be calculated as follows:

$$E \approx \frac{1}{\eta_S - \eta_D}\left[\eta_D (R-AV) + \eta_S (C-W)\right]$$

This method has the advantage of giving a sense of the possible consequences of recycling.

Conclusions: The author concluded that indirect effects of open-loop recycling can be estimated based on the price elasticities of the supply and demand of the recovered material, when the recovery rate is affected by economic forces. The main challenges of the proposed model are that 1) the price elasticities can vary widely and tend to be difficult to obtain, and 2) it could be difficult to identify correctly the affected markets and competitive virgin production.

S7. ISO 14049 Examples of allocation Procedures for recycling

Document Information

Full reference:	International Organization for Standardization (ISO). 2000. *Environmental management — Life cycle assessment — Examples of application of ISO 14041 to goal and scope definition and inventory analysis*. ISO/TR 14049. Geneva: International Organization for Standardization.
How to obtain:	Purchase from ISO: http://www.iso.org/iso/catalogue_detail?csnumber=29834
Paper grades:	General
Classification:	
Perspective:	General
Objective:	General
Function:	General
Geography:	General

Summary

The ISO 14049 technical report provides examples of application for goal and scope definition and inventory analysis in LCA. Among these examples, two specifically deal with open-loop recycling and are presented here: an example application of the "number of subsequent uses" method, and an example application of the closed-loop approximation for open-loop system.

1. The "Number of Subsequent Uses" Method

The report illustrates the "number if subsequent uses" method for open-loop recycling using a hypothetical kraft bleached paperboard (KBPB) product system. The allocation procedure is based on both physical properties and the number of subsequent uses of the recycled and can be described in Figure B-3. These steps are further described below.

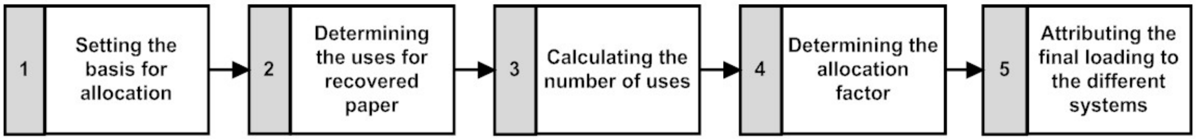

Figure B-3 Stepwise Procedure for Applying the Number of Subsequent Uses Allocation Procedure to Pulp and Paper Products (ISO 2000)

Setting the Basis for Allocation: The basis upon which the allocation factor is made—that is, the total loading which will be allocated between the primary product and the products derived from recycled fibres—reflects the loadings associated with the primary (original) product system, through the end of product life.

Determining the Uses for Recovered Paper: This step consists of identifying the possible uses for recovered paper. There are usually two categories for recovery: 1) usage in tissue products which are used once and then discarded, and 2) usage in other products which are likely to be recovered after use. As illustrated in Figure B-4, in the KBPB example, it is assumed that 30% of the KBPB is discarded (landfill or incineration) and that 70% is recovered (z1 = 0.70). Of this 70%, 25% is recovered into tissue products (u12 = 0.25) and 75% (u13 = 0.75) into other products which practice either closed- or open-loop recycling. To facilitate the calculations, it is assumed that all yields are equal to 1.0 (y2 = y3 = 1.0).

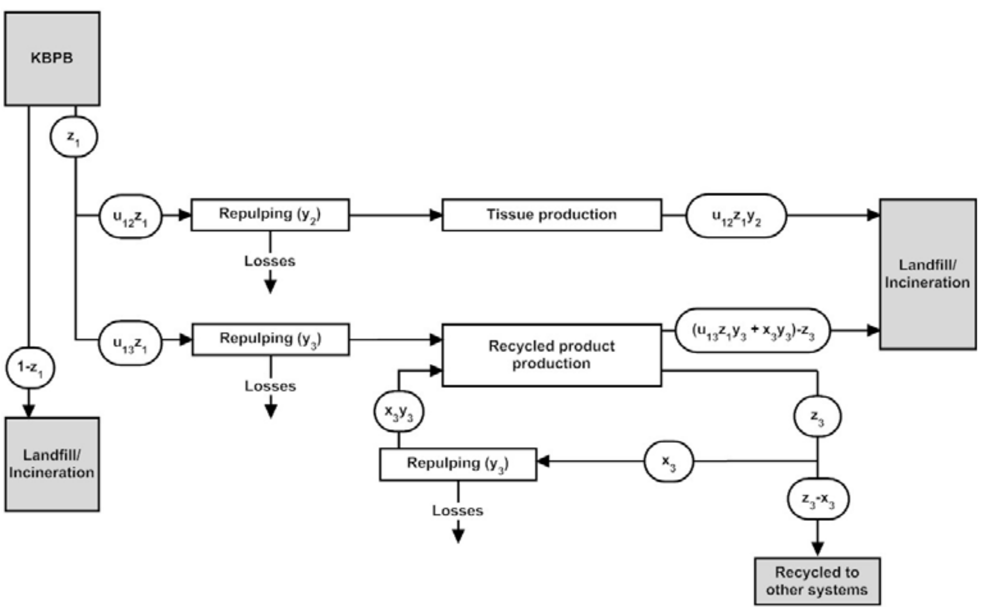

Figure B-4 Subsequent Uses of KBPB (ISO 2000)

Calculating the Number of Uses: The following variables are defined.

u: number of uses

z_1 : fraction of primary product which is recovered after a first use and then recycled

u_{12} : fraction of z_1 fibres which are recycled into tissue

u_{13} : fraction of z_1 fibres which are recycled into products that will ultimately be recycled

y_2 : yield of repulped fibres for tissue production
y_3 : yield of repulped fibres for recycled products
z_3: fraction of recycled product which is recycled again
x_3: fraction of recycled product which is recycled in a closed loop

In the example, it is assumed that z3 = x3 = 0.50 (i.e., no open-loop recycling of post-consumer fibres). The number of uses is calculated as follows:

u=	1	(first use of the primary product recycled, u1)
	$+ z_1u_{12}y_2$	(tissue use)
	$+ z_1u_{13}y_3$	(recycled product use; the first pass)
	$+ z_1u_{13}y_3(z_3y_3)$	(recycled product use; the second pass)
	$+ z_1u_{13}y_3(z_3y_3)^2$	(recycled product use; the third pass)
	……………..	……………..
	$+ z_1u_{13}y_3(z_3y_3)^{n-1}$	(recycled product use; the nth pass)

Knowing that the Maclaurin series for (1-α)-1 is [1 + α + α_2 + α_3 + … α_n], then

$$u \approx 1 + z_1\left[u_{12}y_2 + \frac{u_{13}y_3}{1\text{-}z_3y_3}\right]$$

In the KBPB example,

$$u \approx 1 + 0.70\left[0.70 \times 1.0 + \frac{0.75 \times 1}{1 - 0.5 \times 1.0}\right] = 2.225$$

Determining the Allocation Factor: If a fraction z_1 of the total production of virgin paper (KBPB, in this example) is recovered for subsequent uses in other product systems, then (1 - z_1) of the total burden remains in the primary (original) system, and z_1 of the total burden goes to all product uses (including the first use). The virgin allocation factor (fraction of virgin production environmental load allocated to virgin production, A_V) is calculated this way:

$$A_v = 1\text{-}z_1 + \frac{z_1}{u}$$

The portion allocated to the subsequent uses (A_R):

$$A_R = z_1\frac{(u-1)}{u}$$

For the KBPB example,

$$A_V = 1 - 0.70 + \frac{0.70}{2.225} = 0.61$$

$$A_R = 0.70\frac{(2.225\text{-}1)}{2.225} = 0.39$$

Attributing the Final Loading to the Different Systems: For the primary (original) system, all the loadings per functional unit are multiplied by the allocation factor A_V (0.61, in the example of KBPB). This illustrates the significance of open-loop recycling on the life cycle inventory results. An appreciable fraction of the primary (original) product system is passed on to the totality of the recycled product systems, expressing the fact that the recovered paper is treated as valuable co-product rather than a valueless waste.

2. The Closed-Loop Approximation

The ISO 14044 standard specifies that a closed-loop approach applies to open-loop recycling only if no changes occur in the inherent properties of the recycled material. According to the closed-loop approximation, the product system supplies secondary raw material to a pool and is supplied with secondary material from the pool. If the import and export of secondary raw material between the pool and the product system are equivalent, there is no problem in modelling the product system as a closed-loop system. In the case where there would be a net input or output of raw materials, this should be dealt with using an open-loop procedure because there is an allocation problem concerning the effects of these exports or imports. If system expansion was used, the boundary would be increased to include the potential effects. The closed-loop approach is an attempt to approximate this system expansion by adjusting the technology split of virgin production and recycled production within the boundary of the studied product. This assumes that the virgin production and recycling production are identical or not very different in the product-specific system and the rest of the market for the recovered material, and that the inherent properties of the virgin and recycled pulps are identical or similar.

In the case where there is a net export, as illustrated in Figure B-5a, the closed-loop approximation assumes that this export is used internally to displace virgin material. The case where there is a net import of secondary material, as illustrated in Figure B-5b, is not discussed in ISO 14049 (ISO 2001), but it can be assumed that the same procedure applies. Since the product system studied is in deficit of secondary material, there is a need to import more from other systems and it is assumed that this decrease of secondary material available for other systems will need to be compensated by virgin material. This is represented in the closed-loop approximation by increasing the production of virgin pulp and decreasing the production of recycled pulp.

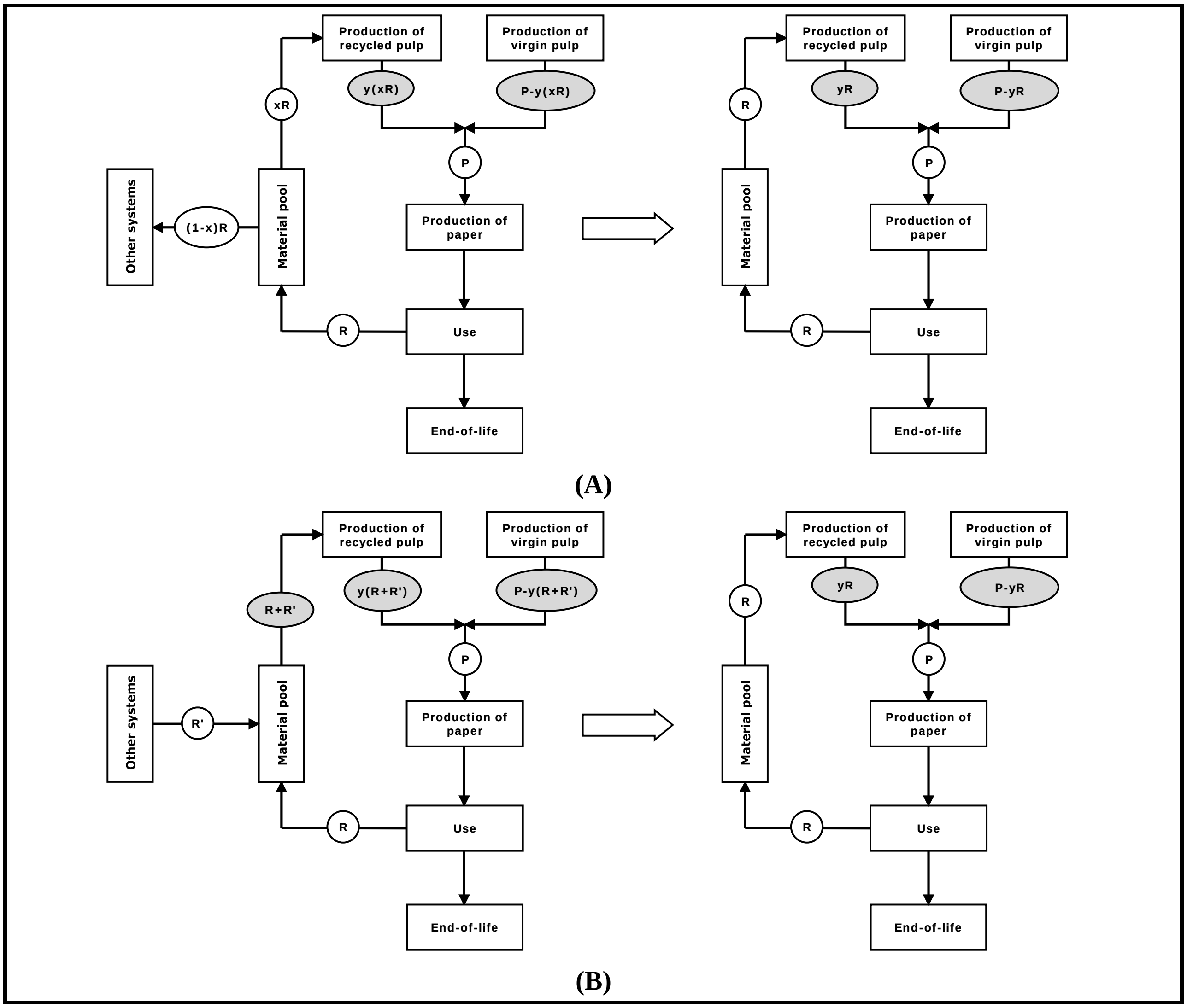

Figure B-5 Interpretation of the ISO 14049 for Closed-Loop Approximation for the Case Where a) There is a Net Export of Recovered Fibre, b) There is a Net Import of Recovered Fibre (adapted from ISO 2000)

[Left: real system. Right: closed-loop approximation. **P:** Total pulp production, **R:** Secondary material from other system, **x:** Fraction of secondary material from the product system which is used in the product system, **y:** Recycled pulp production yield]

S8. A Mathematical Model for Material Recovery, Recycling and Cascaded Use
S9. Application to Graphic Paper

Document Information

Full reference: **S8:** Mellor, W., Wright, E., Clift, R., Azapagic, A. and Stevens, G. 2002. A mathematical model and decision-support framework for material recovery, recycling and cascaded use. *Chemical Engineering Science* 57(22-23):4697-4713.
S9: Hart, A., Clift, R., Riddlestone, S. and Buntin, J. 2005. Use of life cycle assessment to develop industrial ecologies—A case study: Graphics paper. *Process Safety and Environmental Protection* 83(4B):359-363.

How to obtain: **S8:** Purchase from www.sciencedirect.com
S9: Purchase from www.sciencedirect.com

Paper grades: Uncoated freesheet

Classification:

Perspective: Societal

Objective: General

Function: Production of paper product for a certain usage

Geography: UK

Summary

Proposed model: In this paper, a model that builds on the concept of industrial ecology for cascade material was proposed. It is illustrated in Figure B-6.

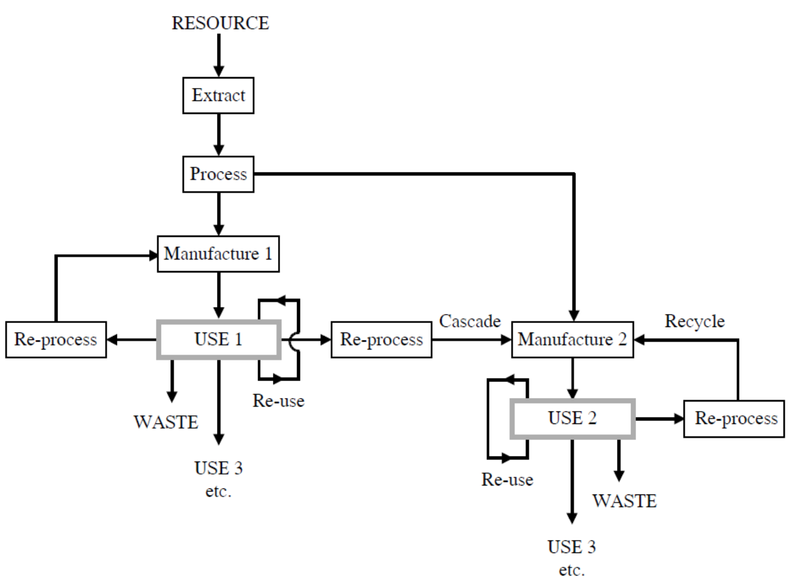

Figure B-6 Use of Cascade Material in Industrial Ecology (Mellor et al. 2002)

This model includes the subsequent uses of the material (or cascade of uses) in a series of different applications which progressively have lower performance. The objective of the proposed model is to support complex decisions in which economic and environmental objectives may have to be traded off for selecting materials and designing products for recovery and re-use. Each material is tracked as it passes through a sequence of activities. Changes in material properties are modelled, along with economic costs and environmental burdens and/or impacts.

Case study: The paper also illustrated the model using a case study. The objective of the case study was to analyze the possibility of recovering one form of paper product—high quality office graphics paper—and recycling it into graphics paper (i.e., no down-cycling) in the city of London. Paper would be collected in London and manufactured in a recycled paper mill located within 100 km (local paper for London, see Figure B-7).

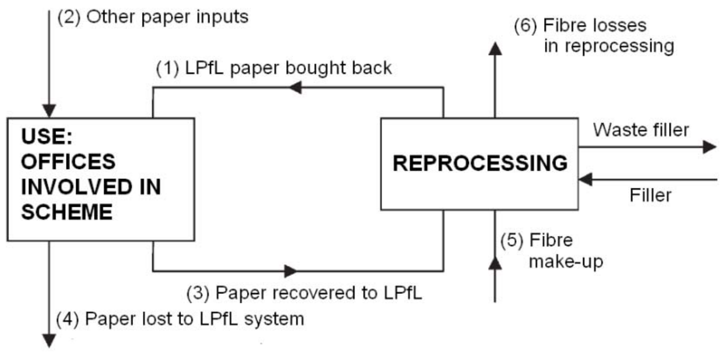

Figure B-7 "Local Paper for London, LPfL" Concept (Hart et al. 2005)

The problem was defined as follows:

1): paper delivered to participating offices in London (= 1 tonne);

2): paper delivered from other source (X) from which only a fraction **s** is of sufficient quality to be recovered and is included;

3): paper returned for reprocessing r(1 + sX) tonnes:

4): paper leaving the system as correspondence to non-participating offices, waste for down-cycling, energy recovery or landfill [(1 - r) + (1 - sr)X];

5): assuming a yield of **t** the recovered fibre produced is tr(1 + sX);

6): make-up fibre **M** is 1-tr(1 + sX).

For the case study, it was assumed r = 0.85 and t = 0.79. Using this estimate, make-up fibre would not be required in the system if the paper delivered from other sources is more than half the paper from recovered fibre produced within the system (i.e., under these conditions, import of paper from other sources would make up for losses in the system. This model does not account for degradation of the fibre with subsequent recycling but can be modified to include the average fibre age N (number of times a fibre is recycled)

$$N = \frac{a}{(1\text{-}ab)}$$

where **a** is the fraction of post-use paper in the feedstock to the recycling mill (i.e., M = 1 – a) and **b** is the proportion of recycled fibre in the recovered paper (i.e., a fraction (1 - b) is paper which enters from a different source and has been processed once only). The value of b depends on the paper from other sources. If this stream contains a fraction q of unrecycled fibre, then

$$(1\text{-}b) = \frac{qrsX}{r(1+SX)}$$

and

$$b=\frac{1+(1\text{-}q)}{1+SX}SX$$

Assuming the national average recovered content of uncoated freesheet printing and writing paper for other fibre inputs (9%) and that there is no virgin fibre make-up introduced, the average fibre age would be N = 3.3, which is considered acceptable. If the other fibre inputs contain more than 25% recovered fibre content, then virgin make-up needs to be added.

This approach has been applied sequentially with LCA to compare different waste management alternatives. It was shown that closed-loop recycling of office paper shows significant benefits compared to traditional down-cycling and burning with energy recovery from an energetic perspective.

Notes

- A yield of 79% is high for production of office paper from recovered fibre in North America.
- There is insufficient detail in the publication to evaluate the results obtained. However, the high yield for recycling may partially explain the result.

S10. MATERIAL FLOW MODELLING AND LCA

Document Information

Full reference: Nyland, C.A., Modahl, I.S., Raadal, H.L. and Hanssen, O.J. 2003. Application of LCA as a decision-making tool for waste management systems—Material flow modelling. *International Journal of Life Cycle Assessment* 8(6):331-336.
How to obtain: Purchase from www.springer.com
Paper grades: Cardboard
Classification:
Perspective: General
Objective: Comparison of end-of-life options
Function: Production of a paper product for a certain usage
Geography: General

Summary

Objective: A typical product LCA generally uses some form of allocation to separate the life cycle of one product from another in cases where component materials are recycled. Also, when system expansion is used for comparing waste management options, it is often assumed that the material is recycled only once. Based on this, the focus of this paper was on the life cycle of the material rather than that of the product, including its multiple reuses. In this case, allocation is not required.

Method proposed: The proposed method is depicted in Figure B-8. Using this approach, if a mass fraction **X** of a given material is recycled **n** times, the amount of virgin material avoided **R** is

$$R=MX_1+MX_2+MX_3+\ldots+MX_1X_2X_3\ldots X_n$$

where M is the mass input of the material. If the fraction recycled is the same in each loop, then **R** is

$$R=M\sum_{n=1}^{\infty}X^n$$

The total amount of material function **T** is

$$T=M+MX_1+MX_2+MX_3+...+MX_1X_2X_3...X_n$$

If the fraction recycled is the same in each loop, then

$$T=M+M\sum_{n=1}^{\infty}X^n$$

For a large number of reused of the material, **T** is

$$\lim_{n\to\infty} T=\frac{M}{1\text{-}X}, 0<X<1$$

The model can also be used for a fixed number of recycling loops.

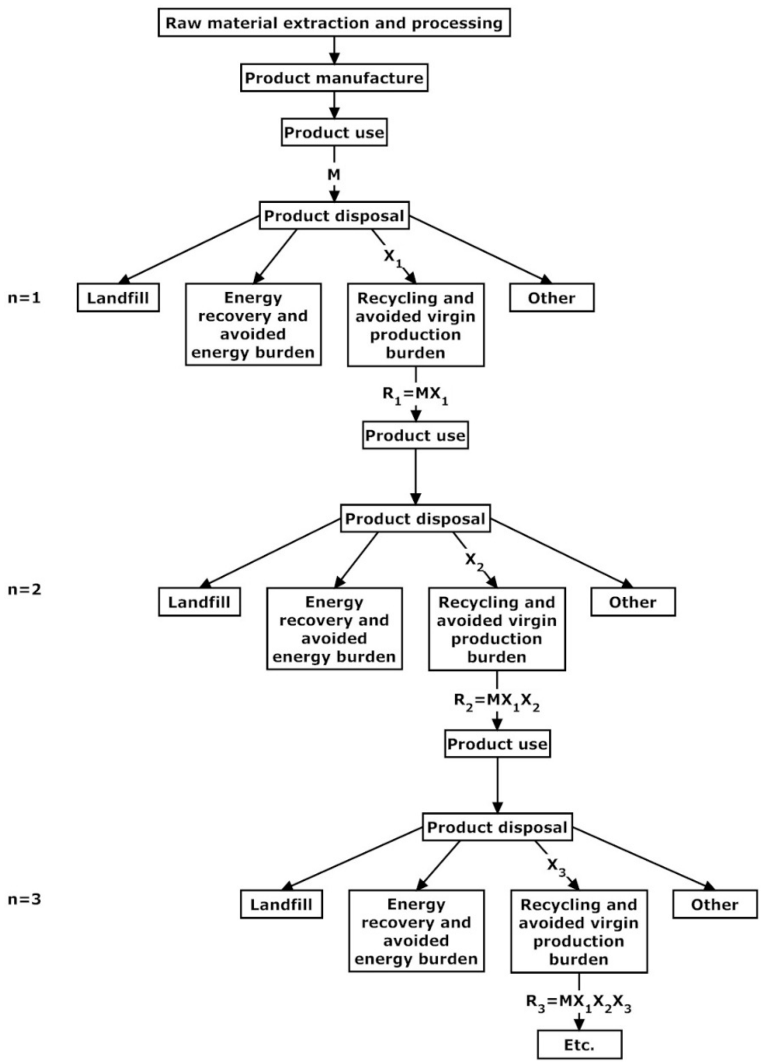

Figure B-8 Material Flow Approach to Recycling (Nyland et al. 2003)

Case study: The proposed approach was applied for a cardboard case study. It was shown that if a recycling rate as high as 80% is achieved for corrugated cardboard and the material is reused up to five times, for every 1 kg of material that enters the system it results in 3.69 kg of material function. It was also shown that energy recovery is the most favourable waste management option in the case where only one recycling loop is considered, but that recycling becomes the best option if the maximum of five reuses is considered.

B.2 LITERATURE REVIEWS

S11. COMPARISON OF GLOBAL WARMING AND TOTAL ENERGY USE OF WASTE MANAGEMENT STRATEGIES FOR PAPER

Document Information

Full reference:	Björklund, A. and Finnveden, G. 2005. Recycling revisited—Life cycle comparisons of global warming impact and total energy use of waste management strategies. *Resources, Conservation and Recycling* 44(4):309-317.
How to obtain:	Purchase from www.sciencedirect.com
Paper grades:	Paper and paperboard products
Classification:	
Perspective:	Societal
Objective:	Comparison of waste management options
Function:	Management of used paper product
Geography:	Various countries in Europe and Australia

Summary

Objectives: LCAs comparing material recycling to incineration and landfilling were reviewed with the aim of determining the extent to which the results align with each other and whether generally applicable conclusions can be drawn.

Methodology: The review was limited to studies that 1) were based on assessing individual waste components, 2) were transparent, 3) that used a system boundary approach that broadened the system to include any avoided burden, and 4) were published in scientific journals. In total, 10 studies were included, which accounted for 40 different scenarios. Only total energy use and global warming impact categories were evaluated.

Main results: The review found that

- recycling generally uses less total energy than burning and landfilling;
- more energy can be saved by displacing mechanical pulp than chemical pulp;
- global warming results depend on the energy source avoided by burning recovered paper;
- burning the used paper generally presents better results when fossil fuels are displaced;
- results are very sensitive to small changes in the system; and
- landfilling always produces the largest energy use and global warming results.

Conclusions: The findings of the literature review indicated that producing materials from recycled resources is less energy-intensive than from virgin resources, with less clear results for paper products for which it is harder to make a judgement in differentiating the results for recycling versus burning.

S12. Paper and Cardboard: Recovery or Disposal
S13. Paper Waste: Recovery, Incineration or Disposal
S14. LCA Boundary Conditions for Paper Waste Management

Document Information

Full reference:	**S12:** European Environment Agency (EEA). 2006. *Paper and cardboard — recovery or disposal?* EEA Technical Report No 5/2006. Copenhagen: European Environment Agency. **S13:** Villanueva, A. and Wenzel, H. 2007. Paper waste—Recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management* 27(8):S29-S46. **S14:** Wenzel, H. and Villanueva, A. 2006. The significance of boundary conditions and assumptions in the environmental life cycle assessment of paper and cardboard waste management strategies. An analytical review of existing studies. In *NorLCA 2006 Symposium*. Lund, Sweden: Nordic Life Cycle Association.
How to obtain:	**S12:** http://www.eea.europa.eu/publications/technical_report_2006_5 (accessed January 2011) **S13:** Purchase from www.sciencedirect.com **S14:** http://www.dtu.dk/upload/subsites/norlca/proceedings%202006/wenzel%20and%20villanueva.pdf (accessed January 2011)
Paper grades:	Paper and paperboard products
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Management of used paper products
Geography:	Various countries in Europe, Australia, and US

Summary

Objectives: The objectives of these studies were to 1) identify and undertake a critical review of published LCA studies on alternatives for managing waste paper, and 2) identify and assess the parameters that are the most significant for the conclusions. Cost-benefit analyses (CBAs) were also reviewed.

Methodology: The focus was on LCAs whose goal is to support the selection of a strategy for the management of waste paper. As much as possible, studies consistent with the ISO LCA standard were reviewed.

Main results: The first step was to identify key issues in evaluating waste management strategies for paper. The issues were divided into categories: system boundary, impact assessment, data and paper grade (more details in Section 4.2). Assumptions made regarding the identified system boundary issues varied significantly in the reviewed study. The review highlighted that energy consumption was generally the most important factor in contributing to environmental impacts in the reviewed studies and indicated that all reviewed studies included an energy consumption indicator. Impact categories considered included global warming, acidification, nutrient enrichment (eutrophication) and photochemical ozone formation (smog). The reviewed studies showed that virgin fibre processing generally produced more polluted wastewater discharges than recovered fibre processing. Few analyses included alternative management of the forest area and of the wood. The reviewed studies also showed that transportation was not an important factor for the results. While all reviewed studies comparing recycling with landfilling of used paper concluded that recycling was the option that created the lowest environmental impacts, the ranking of recycling and burning was sensitive to the assumptions regarding the exports of energy from burning. In general, however, recycling showed better performance than landfilling. Some studies recognized the importance of incremental additional virgin fibre input to maintain the fibre cycle and thus made some adjustment to the substitution ratio (i.e., 1 tonne of recovered fibre cannot substitute 1 tonne of virgin fibre). CBA-related results were more variable.

Conclusions: The review concluded that most scenarios included in the reviewed studies indicated that recycling is the optimal management strategy from an environmental standpoint (very clear when compared to landfilling but less clear when compared to burning) despite differences in geographic conditions and definition of system boundaries. LCA results from different studies were not significantly different. The benefits were more pronounced for the energy use indicator (and other related indicators) and for wastewater discharges.

S15. LCA and the Sustainability of Paper Recycling

Document Information

Full reference:	Grieg-Gran, M. 1995. LCAs of paper product—What can they tell us about the sustainability of recycling. In *Life-Cycle Analysis—A Challenge for Forestry and Forest Industry* (Proceedings of the International Workshop organized by the European Forest Institute and the Federal Research Centre for Forestry and Forest Products, EFI Proceedings No. 8), ed. A. Frühwald, B. Solberg, 123-134. Hamburg, Germany.
How to obtain:	http://www.efi.int/files/attachments/publications/proc08_net.pdf (accessed February 2011)
Paper grades:	Various grades
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Management of used paper product
Geography:	Europe and US

Summary

Objectives: The objective of this paper was to review LCA studies which compared paper recycling and energy recovery options to determine their relative sustainability.

Main findings: An initial analysis of the literature by environmental non-governmental organizations indicated the following stakeholder concerns regarding paper recycling and incineration:

- pressure on natural resources;
- water use and energy;
- toxic impacts related to deinking;
- metals emissions resulting from incineration; and
- local nuisances caused by landfills and incinerators.

In their paper, the authors attempted to correlate LCA findings with these concerns. The studies they reviewed largely showed that energy recovery appears to be a better option than recycling,[9] which is in contradiction with stakeholder concerns.

- Pressure on natural resources: Most reviewed studies did not assess the effect of forestry operations on the environment. For this reason, the concern related to the pressures on natural resources is not addressed in this analysis. On the other hand, one of the reviewed studies argued that recycling would reduce the demand for forest thinning. The authors underlined that, even if there were agreement within the reviewed studies regarding the positive or negative effect of

[9] Most studies reviewed adopted a flow accounting approach to biogenic carbon.

forest operations on natural resources, it is doubtful that LCA would be sufficient to fully address this issue.

- Energy use: LCA can be used to compare the energy used in different paper waste management scenarios. The reviewed LCAs showed that recycling generally reduces the total energy consumption but usually involves a switch from biomass to fossil fuel energy. It was also discussed that the energy question is relevant for incineration scenarios since the energy produced could be used to substitute for another source of energy. The magnitude of the benefits strongly depended on the type of energy (i.e., fuel type and whether it is as power or heat) substituted.
- Water use: Very little attention was given to water use in the reviewed LCAs.
- Toxic impacts from deinking: Very little attention was given to this issue.
- Incineration impacts: In the reviewed LCA studies, the focus was on emission of carbon dioxide, sulphur dioxide nitrogen oxides and particulates. Very little attention was given to the other emissions (e.g., metals).

In addition, the author highlighted that LCA does not address the social and economic impacts of the various waste management options.

B.3 CASE STUDIES

When reviewing case studies, special attention was paid to their treatment of the identified key issues.

1) Modelling of forest management activities
2) Alternative use of the forest land and of the wood
3) Treatment of sawmill co-products
4) Energy use during virgin and recovered fibre processing
5) Energy exports at virgin fibre processing
6) Handling of rejects from recovered fibre processing
7) Landfill emissions
8) Energy exports related to burning waste paper
9) Allocation strategy for recycling
10) Substitution effects
11) Biogenic carbon cycle
12) Data gaps and quality
13) Average and marginal data for electricity production
14) Land use impacts
15) Toxicity-related impacts

If a given key issue is not mentioned in the following summaries, it is because it was not specifically discussed in the case study summarized.

S16. LCA EVALUATION OF PAPER WASTE MANAGEMENT OPTIONS IN ITALY

Document Information

Full reference: Arena, U., Mastellone, M.L., Perugini, F. and Clift, R. 2004. Environmental assessment of paper waste management options by means of LCA methodology. *Industrial and Engineering Chemistry Research* 43(18):5702-5714.

How to obtain: http://classes.engr.oregonstate.edu/engr/fall2006/engr350/Now%20What/IECR%20Paper%20Recycling%20Options.pdf (accessed February 2011)

Paper grades: Paper and board packaging

Classification:

Perspective: Societal

Objective: Comparison of end-of-life options

Function: Management of used paper product

Geography: Italy

Summary

Objective: The objective of this study was to evaluate the environmental performance of the overall Italian system for treating paper and board packaging waste collected from both household and commercial premises.

Functional unit: 1.17 t of paper and board packaging waste collected as a single material stream (with a moisture content of 15%), to produce 1 t of paper and board for packaging (with a moisture content of 7%). See "Recycling allocation" below.

Scenarios: Three different scenarios for the management of paper and board packaging in Italy were evaluated: 1) landfill only, 2) recycling back into paper and board for packaging, and 3) incineration with electricity generation. The fibre was assumed to have originated in Sweden, which is the source of most of the fibre used in Italy, with electricity produced from waste displacing production by the existing Italian electricity system.

System boundary and allocation: An avoided burden approach was used for energy production and recycling.

Treatment of key issues[10]

Alternative use of the forest land and of the wood: No use assumption.

Energy use: Virgin fibre processing occurs in Sweden (power grid is mostly hydro and nuclear), and recovered fibre in Italy (carbon-intensive power grid). Heat requirements for recovered fibre processing are fulfilled mainly through fossil fuels.

Recovered fibre processing rejects: Waste from reprocessing was assumed to be 50% landfilled and 50% burned with energy recovery.

Landfill emissions: It was assumed that landfills have the following characteristics: 55% of the biogas is collected, 60% of the collected biogas is burned in a gas engine with an electrical conversion efficiency of 35%, the remaining 40% of collected biogas is flared, 50-55% of the biogas is methane, and the time required for the landfill to become fully mineralized is 30 years.

Energy exports/End-of-life: Electricity produced through incineration was assumed to displace an equivalent amount of energy in the Italian average grid.

Recycling allocation: The system was expanded to two functions: the production of packaging paper and the management of packaging waste (see Figure B-9). This is the equivalent of assuming that the paper is recycled in a closed-loop fashion.

[10] The key issues related to impact assessment will always be treated in the "Impact assessment" section of the summary.

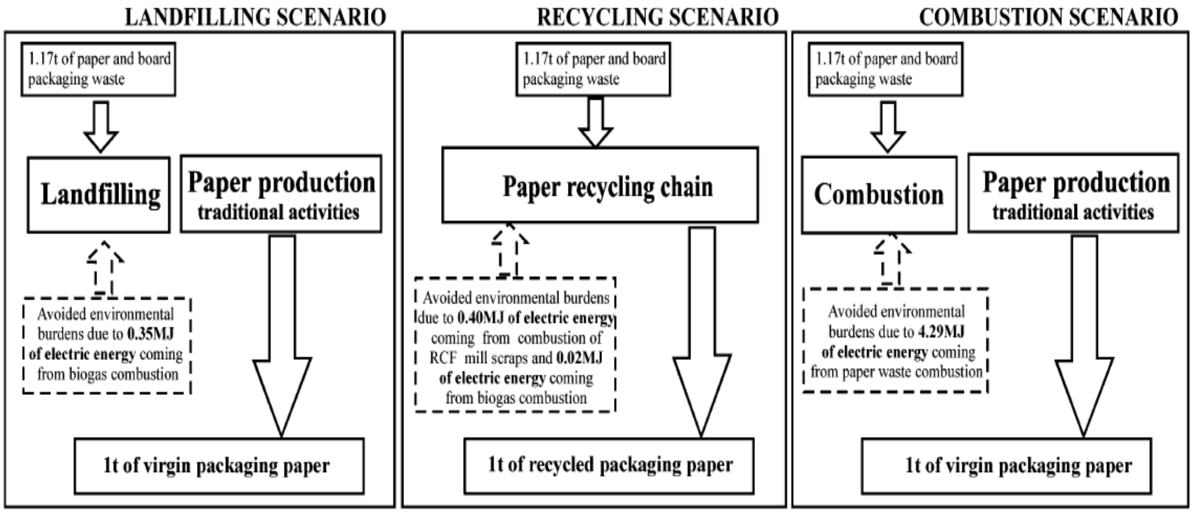

Figure B-9 System Expansion Approach in Arena et al. (2004) Case Study

Substitution effects: It was assumed that virgin and recycled materials are equivalent substitutable materials.

Biogenic carbon: No accounting of biogenic carbon dioxide emissions was undertaken.

Data for electricity: Average.

Impact assessment: Total and non-renewable energy, global warming, and acidification were calculated. Methods were not specified. Other inventory parameters were also evaluated.

Peer review: Not mentioned.

Main results and conclusions: The main results follow.

- Resource consumption
  - The scenario for combustion with energy recovery showed the lowest total energy consumption.
  - The scenarios related to combustion with energy recovery and landfilling consumed the most wood (from sustainably managed forest) and water (in a location were water is not scarce).
- Climate change
  - The recycling scenario resulted in higher GHG emissions from the background system providing the electrical energy and steam used in paperboard reprocessing (background energy system is very carbon-intensive).
  - In terms of avoided emissions, both the landfilling and energy recovery scenarios were credited with significant avoided burdens (substitution of carbon-intensive energy production in Italy). These were large enough to more than compensate for differences in virgin and recovered fibre processing.
  - Transport of virgin paper from Sweden to Italy was not significant to the results.
- Acidification
  - The landfill scenario resulted in the highest acidification results because of virgin fibre processing.
- Others
  - The scenarios incorporating energy recovery generated less non-methane VOCs than other scenarios, but more particulates (the lowest of which were for the recycling scenario).
  - The recycling scenario resulted in the lowest emission of particulates and water pollutants, as well as the least solid waste generation.

Conclusions: The paper concluded that in a high-carbon economy, waste paper should be used as fuel rather than raw material for paper production.

S17. LCA of Newspaper and Magazine
S18. A Method for Evaluating the Land Use Impacts of Forest Operations

Document Information

Full reference: **S17:** Axel Springer Verlag AG, Stora, and Canfor. 1998. *LCA graphic paper and print products (Part 2): Report on industrial process assessment*. Axel Springer Verlag AG, Stora, Canfor.
S18: Axel Springer Verlag AG, Stora and Canfor. 1998. *LCA graphic paper and print products (Part 1): Proposal for a new forestry assessment method in LCA*. Axel Springer Verlag AG, Stora, Canfor.

How to obtain: **S17:** http://www.temap.com/assets_main/documents/LCA_Part_2.pdf
S18: http://www.temap.com/assets_main/documents/LCA_Part_1.pdf
(accessed February 2011)

Paper grades: Newsprint, lightweight coated, supercalendered

Classification:

- **Perspective:** Company
- **Objective:** Comparison of virgin and recycled paper
- **Function:** Production of a paper product for a certain usage

Geography: Germany, Sweden, and Canada

Summary

Objective: This LCA was part of a program by three cooperating industry partners: Stora (pulp and paper production), Canfor (pulp production), and Axel Springer Verlag AG (printer). The objective of the program was to gain knowledge on key environmental issues related to the production chain of print products. The project was divided into two different activities: 1) an LCA of the print products, and 2) development of an impact assessment method for forest operations. Only the former is covered in this review by NCASI. The objectives of the LCA study were to

- develop life cycle inventories for newspaper and magazines;
- identify the processes that contribute the most towards the environmental indicators;
- identify the opportunities for environmental improvements;
- compare the environmental loads of different type of pulp[11];
- compare the environmental loads of different types of paper;
- compare the environmental loads of different print products; and
- compare allocation procedures for open-loop recycling.

Functional unit: Two Axel Springer Verlag products were studied: 1) a newspaper produced by offset printing using newsprint paper (basis weight of 42.5 g/m^2), and 2) a magazine printed in a rotogravure printing process using supercalendered paper for the interior pages (basis weight of 56 g/m^2), and lightweight coated paper for the covers (basis weight of 90 g/m^2). The functional unit for the two products was 1 kilogram of a newspaper and of a magazine in the hand of a reader at the sales point (without inserts).The pulps and papers were also studied separately.

System boundary and allocation: The system starts with the production of wood and ends with the deposition or incineration of the products in a municipal incinerator and the deposition of the “slag”.

[11] Underlined objectives are objectives of interest to this review. The focus of this extended summary is only on those objectives.

Treatment of key issues

Forest management: The authors mentioned that forestry land use has a direct effect on biodiversity. An impact assessment method to assess these direct impacts was separately developed but the effect of applying this on the comparison of deinked versus virgin pulp was not assessed in the study. Other impacts of forest operations were considered.

Alternative use of the forest land and of the wood: Using the cut-off approach for allocation, no forest was allocated to the deinked pulp. However, a forest carbon credit was allocated to deinked pulp (see "Biogenic carbon" below).

Sawmill co-products: Mass allocation was applied.

Energy use: Forest activities occurred in Sweden for newspapers and in Sweden, Germany, and Canada for magazines. Virgin pulping occurred in Sweden for newspapers and in Sweden, Germany, and Canada for magazines. Recycled pulp production occurred in Sweden for newspapers and in Sweden and Germany for magazines. The energy profiles reviewed included

- integrated kraft mills (mostly biomass fuels); and
- TMP and DIP (mix of fuels).

Energy exports/Pulping: Electricity was sold from kraft and TMP mills.

Recovered fibre processing rejects: DIP sludges were burned.

Recycling allocation: Two allocation procedures were compared: the cut-off method, and the "quasi-co-product" method (see box below).

Substitution effects: 1 kg of virgin pulp was compared with 1 kg of deinked pulp.

Biogenic carbon: To incorporate the renewability of the resource (wood), a negative emission factor was introduced for CO_2 for wood and for waste paper:

- 1 kg wood: -1.811 kg CO_2; and
- 1 kg deinked pulp: -1.739 kg CO_2.
- This negative emission factor is transmitted/communicated through the entire fibre life cycle and can result in negative CO_2 emissions at the beginning of the life cycle. If the downstream printing processes are considered, the negative CO_2 emission is reduced to zero by burning or degradation of the products. The share of the products going to the waste paper keeps its negative CO_2 emission. The remaining CO_2 emissions at the end of the life cycle corresponds to the cumulative CO_2 emissions of all production processes.

Data for electricity: Average.

Impact assessment: The assessment was performed using the CML and Eco-Indicator 95 methods. The CML method was modified to include an impact assessment score for AOX. A new method for land use was developed.

Peer review: The study was reviewed by two experts of the Institute of Wood Science and Technology of the University of Hamburg.

Main results and conclusions: The authors found that the use of DIP products reduces the environmental loads of paper grades compared to the use of virgin pulp. This effect is independent of the allocation method applied. The study acknowledged a lack of data about the treatment of DIP sludge. The energy production was a significant contributor to the results. All processes occurring in Germany (versus Canada and Sweden) carried a high environmental load.

In addition, the authors proposed a new method for evaluating the land use impacts of forest operation and applied this method to different type of pulps. Since they used only the cut-off method in this exercise, no land use impacts were assigned to the pulp made of recovered fibres.

THE QUASI-CO-PRODUCT ALLOCATION METHOD

The quasi-co-product allocation method considers the entire life cycle of the fibre as one process for which several quasi co-products are produced (one per fibre use). For instance, if the fibre is reused twice, then there are three quasi-co-products: the virgin product and the two recycled products. The total environmental load of the whole aggregated process (life cycle of the fibre) is summed up and allocated to the quasi-co-products. Classical process allocation rules can be used. The original method allocates the total load based on the mass of the different co-products. While the models it produces may be complicated and may sometimes need some simplification, the main advantage of the method is that it more accurately reflects the entire system. As an additional benefit, the use of the quasi-co-product method allows for expansion of the system to anticipate the effect of higher levels of recovery and recycling – at the very least a highly educational exercise.

In practice, the entire fibre system is complex and it is difficult to calculate the environmental load of the system. For this reason, the following simplification is performed in the case study. Only the production of pulp (virgin pulp and DIP) is included. The processes between the production of virgin pulp and the waste paper collection as a starting point for the DIP process are excluded. This means that all fibre of the same type has the same environmental burden no matter the type of paper in which it was used.

S19. CARBON FOOTPRINT OF THE NATIONAL GEOGRAPHIC MAGAZINE

Document Information

Full reference:	Boguski, T. 2010. Life cycle carbon footprint of the *National Geographic* magazine. *International Journal of Life Cycle Assessment* 15(7):635-643.
How to obtain:	Purchase from www.springer.com
Paper grades:	Coated magazine paper (mostly groundwood)
Classification:	
Perspective:	Company
Objective:	Comparison of virgin and recycled paper
Function:	Production of a paper product for a specified usage
Geography:	US

Summary

Objective: The objective of this study was to calculate the carbon footprint of the *National Geographic* magazine. In addition, the total life cycle energy requirements for the magazine were also computed. The use of 0%, 5%, and 10% recycled fibre content in coated magazine paper was evaluated in this study[12].

Functional unit: The functional unit for the study was 1 magazine. An average magazine in 2008 weighed approximately 349 g.

System boundary and allocation: A cradle-to-grave boundary was used.

Treatment of key issues

Recycling allocation: The cut-off method was used.

Landfill emissions and Biogenic carbon: It was assumed that 60% of the magazines were permanently archived by consumers. The remaining magazines were assumed to be disposed to the municipal solid waste stream (80% landfill, 20% incineration with energy recovery). Sensitivity analyses were performed for the number of magazines recycled. It was assumed that coated magazine

[12] The comparison of these recovered fibre contents is of interest to this current study.

paper in landfills sequestered more carbon, measured as carbon dioxide equivalents, than was released by the degradation of the magazine paper.

Impact assessment: IPCC 100-year factor for global warming (carbon footprint only) was used.

Data: Average.

Peer review: The full report of the study was peer reviewed by Mary Ann Curran (U.S. EPA) and by Reid Miner and Caroline Gaudreault (NCASI).

Main results and conclusions: It was concluded that recycling did not significantly affect the study results for energy or GHG emissions.

S20. Environmental and Economic Impact of Paper Recycling

Document Information

Full reference:	Byström, S. and Lönnstedt, L. 1997. Paper recycling: Environmental and economic impact. *Resources, Conservation and Recycling* 21(2):109-127.
How to obtain:	Purchase from www.sciencedirect.com
Paper grades:	Newsprint, supercalendered paper, lightweight coated paper, office paper, coated woodfree paper, tissue, white lined chipboard, "return fibre chipboard", wrapping paper, white liner, kraft-liner, and fluting
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options for paper/Virgin and recycled paper
Function:	Management of used paper product
Geography:	Western Europe

Summary

Objective: The objective of this paper was to build an optimal fibre flow model that would consider economic and environmental aspects, and fibre quality degradation. Most fibre production (types and amounts) and use in Western Europe were included.

Impact assessment: Individual emissions and each use of non-renewable resources, such as oil and coal, were given an environmental load index value (ELU-index). The ELU-index was developed from a system for Environmental Priority Strategies in Product Design, the so called EPS-system.

Model proposed: Western Europe was divided in two regions: 1) Scandinavia and Continental Western Europe, and 2) the UK. Each region has production resources and a market for paper products and energy. Domestic production was assumed to be used internally or exported to one of the other two regions. Used paper was assumed to be recovered and recycled back into paper and/or burned for energy use. The production value of waste paper was set to depend on the price of fossil fuel and roundwood. The higher the price of oil, the more waste paper was assumed to be recovered for energy purposes. It was assumed that enough capacity exists for deinking and energy production. Twelve different paper grades were considered in the model: newsprint, supercalendered paper, lightweight coated paper, office paper, coated woodfree paper, tissue, white lined chipboard, "return fibre chipboard", wrapping paper, white liner, kraft-liner, and fluting. Typical amounts of fibre, filler and energy consumption were used for each paper grade and five different types of market pulps were included in the analysis.

System boundary and allocation: A cradle-to-grave system boundary was used.

Treatment of key issues

Forest management: Energy used in producing the fertilisers was included.

Alternative use of the forest land and of the wood: The "no use" assumption was applied.

Energy use: Excess energy from virgin pulping was considered to be used in paper production and electricity is produced by back-pressure steam turbines or by condensing turbines.

Energy exports/Pulping: It was assumed that all surplus energy produced at pulping was used in papermaking.

Energy exports/Waste paper burning: It was assumed energy from oil or coal was substituted.

Recycling allocation: System boundary was expanded to include the whole fibre life cycle.

Substitution effects: The age distribution of the fibre in each product was calculated. The recovered fibre yields from different processes, which can be adapted based on recovered fibre age, were included.

Biogenic carbon: A flow accounting approach was used.

Peer review: Not mentioned.

Main results – Economic optimization: When considering that electricity is produced from fossil fuels, an increase in use of recovered fibre (deinked pulp) had the following effects (not observed if it is assumed that electricity is from hydro sources):

- The estimated environmental load was decreased because less thermomechanical pulp was displaced;
- Once all thermomechanical pulp production has been substituted, the economic optimization forced the usage of recycled pulp to substitute other virgin pulp processes which produced excess energy that can be used for drying the paper; and
- With the recycled pulp, this excess energy was not available anymore and had to be replaced by fossil fuel energy, increasing the total environmental load.

Main results – Forcing usage of waste paper in newsprint and office paper: It was shown that the substitution of thermomechanical pulp with deinked pulp exacerbated the estimated environment impacts if hydropower was used to produce newsprint, and diminished estimated environmental impacts if the electricity was based on fossil fuels. In all cases, it was shown that increased used of recovered fibre in office paper had an estimated detrimental effect on the environment.

Conclusions: The model showed no evidence that forcing the recycling of waste paper in products based on chemical pulp was an environmentally friendly policy. Rather, the results supported the energy recovery from waste paper as a substitute for fossil fuels. However, in the studied case, this resulted in decreased revenues for the forest products industry. The estimated effects associated with the use of recovered fibre to displace mechanical pulp were dependent on the type (generation method) of purchased electricity.

S21. LCA Evaluation of Waste Management Options for Newspaper in the Helsinki Metropolitan Area

S22. Combined Ecological and Economic Evaluation of Waste Management Options for Newspaper in the Helsinki Metropolitan Area

Document Information

Full reference:	**S21:** Dahlbo, H., Laukka, J., Myllymaa, T., Koskela, S., Tenhunen, J., Seppälä, J., Jouttijärvi, T. and Melanen, M. 2005. *Waste management options for discarded newspaper in the Helsinki Metropolitan Area - Life cycle assessment report*. FE752. Helsinki: Finnish Environment Institute. **S22:** Dahlbo, H., Ollikainen, M., Peltola, S., Myllymaa, T. and Melanen, M. 2005. *Combining ecological and economic assessment of waste management options—Case of newspaper*. Discussion Paper no. 9. Helsinki: University of Helsinki, Department of Economics and Management.
How to obtain:	**S21:** http://www.ymparisto.fi/download.asp?contentid=34817&lan=en **S22:** http://www.helsinki.fi/taloustiede/Abs/DP9.pdf (accessed February 2011)
Paper grades:	Newsprint

Classification:

Perspective: Societal
Objective: Comparison of end-of-life options
Function: Management of used paper product
Geography: Helsinki Metropolitan Area (HMA), Finland

Summary

Objective: The objectives of the LCA-WASTE project were to develop a methodology for assessing the environmental impacts and costs of alternative waste management solutions and to provide information for waste policy making.

Functional unit: One ton of waste entering the waste management system.

Scenarios: Five options were analyzed. They included various recovery and treatment methods applicable to the newspaper in a separately collected paper fraction and to the newspaper in a mixed waste fraction. The methods considered for the separately collected paper fraction were 1) material recycling, 2) gasification and co-combustion, and 3) incineration. The methods considered for newspaper in the mixed waste were 1) landfilling, 2) mechanical-biological pre-treatment followed by gasification and co-combustion, and 3) incineration. The five options were:

1. The Helsinki Metropolitan Area (HMA) base case system: paper that is collected separately is recycled into newsprint, and paper in mixed waste is landfilled.
2. HMA plans to build new waste management facilities.
    a. Paper collected separately is recycled and paper from mixed waste is subjected to gasification and co-combustion of SRF (solid recovered fuel, containing newspaper and various other materials) sorted from the mixed waste by mechanical-biological pre-treatment;
    b. Same as 2a, but 50% of the separately collected papers is also gasified and co-combusted (gasification, purification of the product gas and co-combustion of the purified gas with pulverised coal and natural gas in a combined heat and power plant).
3. Theoretical scenarios
    a. The separately collected paper is recycled and the paper in mixed waste is burned with energy recovery.
    b. Same as 3a, but 50% of the separately collected paper is also burned with energy recovery.

System boundary and allocation: The system boundary was set from the forest to the end-of-life. Allocation procedures (mainly mass) are used when required. Benefits from exported energy were accounted for using avoided emissions.

<u>Treatment of key issues</u>

Forest management: The modules and unit processes comprising the forestry phase were silviculture, forest growth, sawmill, fuel production, and electricity generation.

Alternative use of the forest land and of the wood: No use.

Sawmill co-products: Mass allocation.

Energy use: It was assumed that virgin and recycled newsprint were manufactured at the same mill, located in central Finland. The average Finnish electricity and heat generation (in the grid) were used as the supply of electricity and heat for the entire product system. When more virgin wood material was used at the paper mill, the electricity consumption of the TMP process increased. The change in the material composition affected the fuel mixture used at the power plant of the mill. When using more virgin wood materials, more biofuels were produced at the paper mill and thus the need for fossil fuels for the power generation at the paper mill decreased.

Landfill emissions: The emissions from the landfill were considered within an infinite time scale, assuming that all the materials landfilled in newspaper would ultimately be released as emissions to air or water. 75% of the landfill gas was collected and flared. Energy was recovered (60% of the energy of methane was converted into heat, 30% into electricity, and 10% lost. It was assumed that the landfill gas contained 54% methane and 46% carbon dioxide.

Energy exports/End-of-life: For cases 2a and 2b, it was assumed that heat energy from coal was substituted. For cases 3a and 3b, two types of incineration facilities were modelled: one producing mainly heat and one producing mainly electricity. In practice, however, heat from incineration would not be used in the municipal district heat network in the Helsinki Metropolitan Area (HMA), since the existing energy network is based on combined heat and power generation. Thus, there is no demand for a new heat-producing facility. Only if there were a demand for heat in the industrial sector, would incineration with the production of heat be a realistic option. On the other hand, electricity generated through waste paper incineration could be used, but there are two facts acting against a new electricity-producing facility in the HMA: the efficiency of the facility would be low, the capital expenditure high. If an incineration facility were built in the HMA, it would most probably act as a waste treatment facility rather than as a form of energy recovery, unless industry could use the heat load from incineration. In this study, two ways of assessing the emissions avoided by energy recovered from wastes were studied, based on using two different fuel mixtures: 1) that used for the average Finnish electricity and heat production, and 2) that used in a local coal-powered CHP plant.

Recycling allocation: In the product systems studied, recycling was modelled as closed-loop recycling. All newspapers collected separately for material recycling in the HMA were returned for deinking and recovery in newsprint manufacturing. The amounts of the other raw materials used for newsprint manufacturing were adapted to the amount of recovered newspaper available for material recovery.

Biogenic carbon: Flow accounting.

Data for electricity: Both marginal and average.

Impact assessment: Three impact assessment methods were used: DAIA (Decision Analysis Impact Assessment), Eco-indicator 99, and EPS 2000 (a systematic approach to environmental priority strategies in product development).

Peer review: Experts from SYKE and VTT provided comments on the report.

Main results and conclusions: Most of the LCI and LCIA results of this LCA study showed that landfilling of newspaper in the untreated mixed waste resulted in higher estimated environmental effects compared to its recovery for energy generation. The three LCIA methods used gave slightly inconsistent results when considering the performance of the various energy recovery options. Incineration resulted in equal or higher estimated environmental effects than landfilling, when looking at the results from the Eco-indicator 99 and EPS 2000. All the LCIA methods showed that co-combustion of newspaper had lower estimated environmental effects than material recycling or incineration if solid recovered fuel (SRF) is used to replace coal as fuel. The performance of an energy recovery option was very much dependent on the possibility for connecting the waste-to-energy facility into the existing energy production system. Transportation was a significant contributor to estimated NOx emissions, whereas the other atmospheric emissions were estimated to be relatively small. None of the LCIA methods used in this study adequately addressed land use aspects. However, because recycling was thought to have a significant effect on forest biodiversity, forest biodiversity was analyzed using the area of used forest. The alternative that scored the best from an environmental standpoint was the second most expensive and the one that scored the worst was the cheapest.

Note

Although landfill emissions were found to be quite uncertain in this particular study, experience has shown that a large proportion of newspapers will not degrade in landfills (USEPA 2006).

S23. LCA OF PRINTING AND WRITING PAPERS IN PORTUGAL

Document Information

Full reference: Dias, A.C., Arroja, L. and Capela, I. 2007. . Life cycle assessment of printing and writing paper produced in Portugal. *International Journal of Life Cycle Assessment* 12(7):521-528.

How to obtain: Purchase from www.springer.com

Paper grades: Printing and writing paper

Classification:

- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options
- **Function:** Production of a paper product for a certain usage

Geography: Portugal and Germany

Summary

Objective: The objectives of the study were to 1) to assess the potential environmental impacts of the printing and writing paper produced in Portugal and consumed in Germany over its entire life cycle, and 2) evaluate the effect on the potential environmental impacts of changing the market where the Portuguese printing and writing paper is consumed (German market vs. Portuguese market). **Note:** These two different markets have different end-of-life conditions.

Functional unit: 1 tonne of white printing and writing paper, with a standard weight of 80 g/m^2, made in Portugal from *Eucalyptus globulus* kraft pulp.

Scenarios: Since two different markets were considered, two different end-of-life conditions were compared. For Germany, the end-of life was 17% landfill, 8% incineration, and 75% recycling in tissue, packaging paper, and graphic paper. In Portugal, the end-of-life was 53% landfill, 18% incineration, 4% composting, and 25% recycling in tissue, packaging paper, and printing and writing paper.

System boundary and allocation: The system boundary was set from the forest to end-of-life. Allocation procedures (mainly mass-based) were used when required. Benefits from exported energy and reduced virgin fibre production were accounted for using avoided emissions.

Treatment of key issues

Forest management: Forest operations were included.

Energy exports/Pulping: Where surplus electricity was produced, the environmental burdens associated with the production of the same amount of electricity in the national grids where the processes take place were subtracted from the inputs and outputs of these processes.

Landfill emissions: Landfill gas was not burned.

Energy exports/End-of-life: In the case where surplus heat/electricity was produced, the estimated environmental burdens associated with the production of the same amount of heat/electricity in the national grids where the processes take place were subtracted from the inputs and outputs of these processes.

Recycling allocation: At the end-of-life, system expansion (avoided burden method) was used for recycling. The enlarged system included the production of paper from recovered fibre and was credited for the same amount of paper from virgin fibre. Note, as discussed in Section 4.3.3, this is usually done without respecting ISO 14044 additivity requirement.

Substitution effects: The fluxes of paper going to recycling were allocated to different paper grades: 85% in tissue paper, 5% in graphic paper, and 15% in packaging papers for Germany; 52% in tissue paper, 39% packaging paper, and 9% in printing and writing papers for Portugal. It was assumed that the use of recycled paper displaces the use of equivalent paper grades made from virgin fibre.

Biogenic carbon: Biogenic emissions were not accounted for.

Data for electricity: Average.

Impact assessment: Global warming, acidification, eutrophication, non-renewable resource depletion, and photochemical oxidant formation were analyzed.

Peer review: No mention.

Main results and conclusions: It was shown in this study that the Portuguese market gave higher estimated environmental impacts for the global warming and photochemical oxidant formation impact categories, because landfilling was the main final disposal alternative for wastepaper, resulting in significant releases of methane. Paper distribution differences had a significant effect on the comparison of both markets.

S24. LCA OF SUPERMARKET CARRIER BAGS

Document Information

Full reference:	Edwards, C. and Meyhoff Fry, J. 2011. *Life cycle assessment of supermarket carrier bags*. SC030148. Bristol, UK: Environment Agency.
How to obtain:	http://www.environment-agency.gov.uk/research/library/publications/129364.aspx (accessed May 2011)
Paper grades:	Bag and sack paper
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Production of a paper product for a certain usage
Geography:	UK

Summary

Objective: This objective of this study, commissioned by the Environment Agency, was to assess the life cycle environmental impacts of the production, use, and disposal of different lightweight supermarket carrier bags, including those made of paper, for the UK. The effect of increasing recycling at the end-of-life was also studied.

Functional unit: Carrying one month's shopping (483 items) from the supermarket to the home in the UK in 2006/07.

System boundary and allocation: Cradle-to-grave boundaries were used.

Treatment of key issues

Landfill emissions: The model included landfill treatment and landfill gas capture (equivalent to 75% over its lifetime) for landfill gas recovery and landfill gas burned in engines generating electricity, which offsets the marginal mix for electricity production of 50% coal and 50% natural gas.

Energy exports/End-of-life: The generation of electricity from both landfill and incineration were accounted for through the avoided production of UK grid electricity.

Recycling allocation and Substitution effects: The expansion of the system boundaries of the study to include avoided products was used to model recycling. It was assumed the recycling of material waste from production and at end-of-life avoids the use of virgin material, which was subtracted from the system. The avoided production of virgin materials was adjusted for any loss in material performance due to the recycling process. It was assumed that the paper bag does not fully degrade in a landfill.

Biogenic carbon: The global warming potential (GWP) of biogenic carbon dioxide was considered to be zero. A sensitivity analysis on this assumption was performed by assigning a characterization factor of 1 to the GWP of biogenic carbon dioxide and a characterization factor of -1 to carbon dioxide absorbed from the air by biomass (such as trees). This sensitivity analysis therefore included biogenic carbon dioxide that is absorbed and released during the natural carbon cycle. The effect of that approach for the recycling scenarios was not assessed.

Data for electricity: Marginal.

Impact assessment: The IPCC global warming potentials and the CML method were used for the following impacts: depletion of abiotic resources, photo-oxidant formation, eutrophication, acidification, human toxicity, aquatic and terrestrial toxicity.

Peer review: The study has been critically reviewed in accordance with ISO 14040. The review panel consisted of

- Mark Goedkoop (chairman), PRé Consultants, Amersfoort, the Netherlands;
- Keith Elstob (co-reviewer), Bunzl Retail, Manchester; and
- Jane Bickerstaffe (co-reviewer), INCPEN, Reading.

Main results and conclusions: It was found that recycling of the paper bag reduced the estimated environmental impact in most of the impact categories considered, including a 21% reduction in GWP. However, recycling caused an increase in fresh water ecotoxicity due to the release of copper to the water during recycling and terrestrial ecotoxicity from composting due to the release of metallic contaminants to soil and water.

S25. LCA OF TISSUE PRODUCTS

Document Information

Full reference:	Environmental Resources Management (ERM). 2007. *Life cycle assessment of tissue products*. Report prepared for Kimberly-Clark. Environmental Resources Management.
How to obtain:	http://www.kimberly-clark.com/pdfs/FinalReportLCATissuePaper.pdf (accessed February 2011)
Paper grades:	Tissue
Classification:	
Perspective:	Company
Objective:	Comparison of virgin and recycled paper
Function:	Production of a paper product for a certain usage
Geography:	North America and Europe

Summary

Objective: The goal of this study was to determine the environmental performance of various tissue products manufactured by Kimberly-Clark (K-C) and the environmental trade-offs associated with the use of virgin fibre and recycled fibre in tissue products.

Functional unit: Functional units were defined based on the different products' functions. They were generally defined as 1 year of use of the tissue product.

System boundary and allocation: Cradle-to-grave boundary was used.

Treatment of key issues

Forest management: The production of raw materials such as hardwood and softwood were included in the study, incorporating the materials and energy used and the emissions related to nursery and timber growth, the use of fuel and subsequent emissions for harvesting equipment, and the landscape and biodiversity impacts of infrastructure.

Alternative management of the forest land and of the wood: In the study, two allocation procedures for recycling were applied (see Recycling allocation below), which had an effect on the alternative management of the forest land. Using the cut-off method, no forest impacts were allocated to the recycled fibre. Using the number of subsequent uses method, a portion of the forest impacts was transferred to the recycled fibre.

Sawmill co-products: Mass allocation.

Energy use: The following was considered regarding energy use: virgin fibre processing is performed through kraft or chemi-thermomechanical pulp in Brazil, Canada, and Scandinavia, and K-C purchases deinked pulp but also waste paper from paper merchants to use in its integrated tissue mills.

Recovered fibre processing rejects: The residuals produced were considered to be either land applied, landfilled, or incinerated.

Landfill emissions: It was considered that no energy was generated from landfilling and incineration of used tissue products. It was initially assumed that 100% of the biogenic carbon within the tissue was degraded to CO_2 and CH_4 within the time frame of the study. This assumption was tested using sensitivity analysis as a result of published research undertaken into the degradation of paper under anaerobic conditions.

Energy exports/End-of-life: No environmental benefits from energy recovery from waste treatment of tissue paper were assumed.

Recycling allocation: The cut-off and number of subsequent use methods were applied and compared.

Biogenic carbon: A flow accounting approach was used and renewable CO_2 was reported separately from fossil CO_2.

Data for electricity: Marginal.

Impact assessment: The following indicators were included: climate change, ozone depletion, photooxidant formation, depletion of abiotic resources, eutrophication, acidification, human toxicity, fossil energy consumption solid waste, and water use. The CML method was used. A sensitivity analysis was performed using the IMPACT 2002+ method.

Peer review: In accordance with the ISO standard for LCA, the study was reviewed by an external review panel consisting of three experts.

Main results and conclusions: Overall, the results indicated that neither fibre type can be considered environmentally preferable. It was shown the both virgin fibre and recycled fibre offer environmental benefits and shortcomings. Results indicated that for impact categories generally associated with fossil fuel combustion, products from virgin fibre had lower estimated environmental impacts. Water use and solid waste results were less straightforward. Water use was generally estimated to be lower for products with high virgin fibre content, compared to the equivalent product with recycled fibres, if the number of subsequent uses method was used. When the cut-off method was used, however, the estimated water use associated with waste paper decreased significantly and was lower than the water consumed for some of the virgin products. Solid waste results were very dependent on the product type. When the CML method was used, the virgin products showed the highest human toxicity impact due to PAH emissions from black liquor combustion. The results of the sensitivity analysis on degraded carbon in landfills were not presented in the final report.

S26. LCA OF ENERGY FROM WASTES – GENERAL RESULTS
S27. LCA OF ENERGY FROM WASTE – LANDFILL COMPARED TO OTHER METHODS
S28. LCA OF ENERGY FROM WASTE – LONG REPORT

Document Information

Full reference: **S26:** Finnveden, G., Johansson, J., Lind, P. and Moberg, Å. 2005. Life cycle assessment of energy from solid waste—Part 1: General methodology and results. *Journal of Cleaner Production* 13(3):213-229.
S27: Moberg, Å., Finnveden, G., Johansson, J. and Lind, P. 2005. Life cycle assessment of energy from solid waste-—Part 2: Landfilling compared to other treatment methods. *Journal of Cleaner Production* 13(3):231-240.
S28: Finnveden, G., Johansson, J., Lind, P. and Moberg, Å. 2000. *Life cycle assessment of energy from solid waste*. FOA-B--00-00622-222--SE fms 137. Stokholm: Stockholms Universitet/Systemekologi and FOA, Forskningsgruppen för Miljöstrategiska Studier.

How to obtain: **S26:** Purchase from www.sciencedirect.com
S27: Purchase from www.sciencedirect.com
S28: http://www.infra.kth.se/fms/pdf/LCAofenergyfromsolidwaste.pdf (accessed February 2011)

Paper grades: Newsprint, cardboard (corrugated and mixed), but disaggregated results are presented only for newsprint

Classification:
- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options
- **Function:** Management of used paper product

Geography: Sweden

Summary

Objective: The paper indicated that it is generally agreed that in the waste hierarchy, waste reduction is the most preferable option from an environmental standpoint. However, the remainder of the hierarchy is often debated, particularly when it comes to incineration for energy and recycling. Also, it is uncertain where biological treatments such as anaerobic digestion and composting should be placed in the hierarchy. The objective of this paper was to assess strategies for treatment of solid waste based on a life cycle perspective.

Functional unit: The functional unit was the treatment of the wastes collected in Sweden during one year.

Approach and scenarios: The treatment methods considered for paper products included incineration with heat recovery, landfilling with landfill gas extraction, and recycling.

System boundary and allocation: A simplified process flow chart for the newspaper recycling system is shown in Figure B-10. The systems were very similar for corrugated board and mixed cardboard.

Treatment of key issues

> **Alternative use of the forest land and of the wood:** It was assumed that when paper products are recycled, less wood is used for production of virgin paper materials. This wood can be left in the forests, but it can also be used for heat production.

Energy use: The following was assumed for energy production related to the different products analyzed.

Purchased electricity: For all products, purchased electricity was assumed to be generated using coal.

Newsprint: For virgin and recycled newsprint production, steam was assumed to be produced in bark- and oil-fired boilers. A significant amount of electricity was used in the virgin newsprint production. However, the part of this electricity that was used in the virgin pulp production process (TMP) was transformed in heat that was subsequently used to dry the paper.

Corrugated board: The recycled versions of the two layers of corrugated board were wellenstoff (corrugated medium) and testliner (linerboard). Energy used in the production of testliner and wellenstoff was from natural gas, heavy and light fuel oil, diesel oil, liquefied petroleum gas, and lignite. Energy used in the production of kraftliner (virgin product) and fluting was from natural gas, heavy and light fuel oil, diesel oil, coal (only fluting), peat, bark, and wood chips.

Mixed cardboard: Energy from oil and electricity was assumed to be used in the recycling and virgin processes.

Energy exports/Pulping: Electricity sold to the public grid was recorded as avoided electricity production. The electricity used and avoided was assumed to be coal-based. Some energy from both recycled and virgin corrugated board processes was sold to the grid.

Recovered fibre processing rejects: Process rejects were not included.

Landfill emissions: Two time periods were considered for landfills: the time to reach a steady state (surveyable time period, ST) and the remaining time period (RT) characterized by a full degradation of the waste. Landfills were assumed to have gas collection systems operating during ST, with an efficiency of 50%. The gas collected was assumed to be combusted for electricity (30%) and heat production (60%). Ten percent of the energy electricity and heat was assumed to be lost. Gas that was not collected passed through the soil where 15% of the methane was assumed to be oxidized to carbon dioxide. The CO_2 hence converted from CH_4 was divided into biological CO_2 and fossil CO_2 depending on the origin of the carbon in the methane. Biological carbon was divided into groups: carbon in lignin was assumed to be non-degraded during ST, the carbon in cellulose was assumed to degrade by 70% during ST, and the rest of the biological carbon (easily degradable starch, sugar, fat, and protein) was assumed to be totally degraded during ST. Under the anaerobic conditions assumed for the surveyable time period, various shares of the carbon were converted to carbon dioxide and methane depending on the origin of the carbon. During RT, all fossil carbon was assumed to become CO_2. The only methane produced during RT was derived from 40% of the remaining cellulose carbon.

Energy exports/End-of-life: Energy generated from burning and landfill gas recovery was used as a fuel replacing diesel or for heat and electricity. In this study, electricity generated from hard coal was chosen as the marginal technology. Both forest residues and natural gas were used as the marginal district heating sources in different scenarios.

Recycling allocation: The system expansion approach was used when useful products were produced from the recycling to avoid open-loop recycling allocation. The avoided processes were subtracted from the system boundaries.

Substitution effects: Recycled paper was assumed to replace paper materials of similar qualities made from virgin materials. However, the fibre quality would not be as high for recycled and therefore a larger amount of fibre was assumed for the recycling option.

Newsprint: To obtain similar properties as those for virgin newsprint, 16% of the pulp was from virgin fibres.

Corrugated board: To obtain similar properties to virgin materials ,an extra 10% input of recycled paper was assumed to be needed.

Mixed cardboard: To obtain similar properties as those for virgin cardboard, an extra 15% weight was assumed for the recycled board.

Biogenic carbon: No accounting of the biogenic CO_2 in the base case scenario, flow accounting in the sensitivity analysis.

Data for electricity: Marginal.

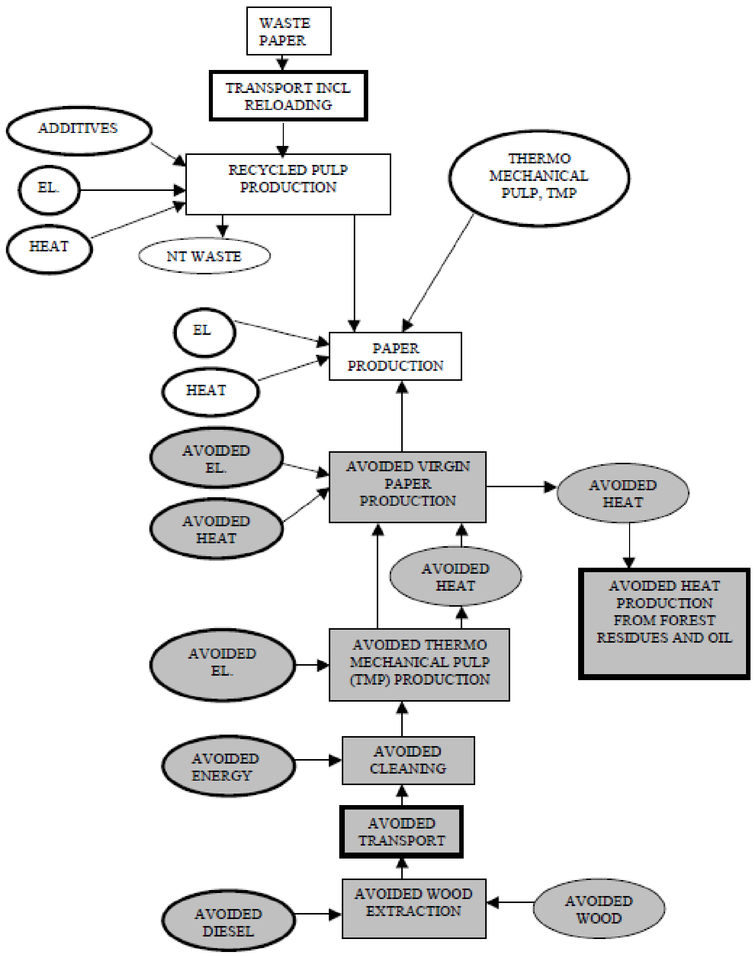

Figure B-10 A Simplified Process Flow Chart for the Newspaper Recycling System (Finnveden et al. 2000)

Impact assessment: Various impact assessment methods were used and compared. The authors highlighted that not all impact categories were equally well covered in the study.

- Total energy, non-renewable energy, abiotic resources, global warming, and acidification were reasonably well covered without significant data gaps.
- The other impact categories (non-treated wastes[13], depletion of stratospheric ozone, photo-oxidant formation, aquatic eutrophication, ecotoxicological impacts, and human toxicological impacts)

[13] Non-treated waste is an impact category including flows that have not been followed to the grave (i.e., no management).

likely had significant data gaps, and therefore the conclusions regarding these impact categories and the overall total weighted results should be viewed with caution.

Peer review: This study is included in this current literature review because the papers were accepted in peer-reviewed journals. However, the full report was not peer-reviewed.

Main results and conclusions:

The results obtained in this study were often negative because of the avoided functions included in the boundaries. A negative result is referred as "savings" by the study authors.

A) Newspapers: The main results obtained follow.

- Recycling BT[14] Incineration BT Landfill
    - **Total energy.** The recycling alternative resulted in lower energy use, predominantly renewable. Less energy was saved using the incineration option. The least energy was saved when landfilling.
    - **Global warming.** Recycling newspaper resulted in the avoidance of CO_2 emissions from electricity use in virgin paper production. Incineration was estimated to cause net emissions of CO_2. The largest net emissions of greenhouse gases were estimated to occur in the landfill alternative, mostly as methane in the surveyable time period.
    - **Acidification**. All treatment options showed savings, the most from recycling a little bit less from incineration, and the least from landfilling.
    - **Sulphur oxides**. The greatest amount of estimated SO_x releases was avoided in the recycling alternative. The major contribution to this was from the avoidance of coal-based electricity when replacing virgin newspaper. Landfill resulted in estimated net emissions of SO_x.
- Recycling BT Landfill BT Incineration
    - **Non-renewable energy.** Recycling saved the most non-renewable energy because energy from coal in the virgin paper production could be avoided. Landfilling also allowed some savings of non-renewable energy through avoided electricity production from coal. Incineration used non-renewable energy from coal.
    - **Abiotic resources.** Same pattern as non-renewable energy.
    - **Non-treated wastes.** More non-treated wastes were avoided than were being produced in the recycling and landfilling cases (more for recycling than for landfill). Incineration resulted in a net generation of wastes.
    - **Nitrogen oxides.** Recycling newspaper led to a net avoidance of NO_x emissions, since the virgin production used more coal-based electricity. Landfilling resulted in a net emission of NO_x released in the surveyable time period. A larger net emission was present in the incineration alternative.
- Incineration BT Recycling BT Landfill
    - **Photo-oxidant formation.** The emissions contributing to photo-oxidant formation avoided in the incineration case were larger than those avoided when recycling. Landfilling resulted in a net contribution to this impact category.
    - **Aquatic eutrophication.** Emissions contributing to aquatic eutrophication (excluding NO_x) were seen to be avoided through incineration. Recycling resulted in an estimated net release of eutrophying substances that was a little smaller than landfilling.
- Incineration BT Landfill BT Recycling
    - **Terrestrial eutrophication from ammonia.** The highest amount of NH_3 was avoided in the incineration alternative. Less was "saved" when landfilling, whereas a net emission occurred in the recycling alternative.

[14] BT: better than.

- Unclear results
    - **Ecotoxicity.** Results obtained depended on the method used. None of the treatment options was found to be the best for all methods.
    - **Human toxicity**. Incineration led to the greatest estimated benefits for all methods used. The ranking of landfill and recycling depended on the method used.
    - **Total weighted results:** Results obtained depended on the method used. None of the treatment option was the best for all methods. Landfill was never found to be the best option, in terms of overall weighted results.

B) Sensitivity analyses:

- Increasing transportation distances: In general, increasing transportation distances was not found to have a significant effect.
- Natural gas displaced by heat produced at incineration and landfill: This scenario changed the ranking of landfilling and incineration for the NO_x, SO_x, and NH_3 indicators.
- Saved forest used for heat: This scenario increased the estimated benefits of recycling. The ranking was altered for photo-oxidant formation.
- Short-term landfill emissions only: In general, this scenario was not found to significantly affect the results.
- Landfills as carbon sinks: Using this assumption, the landfill option was found to have lower impacts than incineration, for the global warming indicator.

C) Other paper grades: In general, the other grades were found to follow the same patterns as those for newspaper. One conclusion of the results presented in this study was that placing landfilling at the bottom of the waste hierarchy may be valid, as a rule of thumb. When a shorter time perspective was used for landfills and they were considered to be carbon sinks, then landfilling was found to result in lower impacts than incineration.

S29. Choices in LCA for Increasing the Deinking Capacity at a Newsprint Mill
S30. System Boundary in LCA for Increasing the Deinking Capacity at a Newsprint Mill

Document Information

Full reference:	**S29:** Gaudreault, C., Samson, R. and Stuart, P.R. 2010. Energy decision making in a pulp and paper mill: Selection of LCA system boundary. *International Journal of Life Cycle Assessment* 15(2):198-211. **S30:** Gaudreault, C., Samson, R. and Stuart, P. 2009. Implications of choices and interpretation in LCA for multi-criteria process design: deinked pulp capacity and cogeneration at a paper mill case study. *Journal of Cleaner Production* 17(17):1535-1546.
How to obtain:	**S29:** Purchase from www.springer.com **S30:** Purchase from www.sciencedirect.com
Paper grades:	Newsprint
Classification:	
Perspective:	Company
Objective:	Comparison of virgin and recycled paper
Function:	Production of a paper product for a certain usage
Geography:	Canada

Summary

Objective: The objective of this paper was to assess the effect of different choices in LCA using a case study aimed at increasing the consumption of recovered fibre and cogeneration at an integrated newsprint mill. In this literature review, the emphasis was on the increased consumption of recovered fibre and not on cogeneration.

Functional unit: The functional unit was the production of 1 air-dried metric tonne of newsprint.

System boundary and allocation: Different approaches were taken to set the system boundaries: an attributional approach (ALCA, cradle-to-gate; from forest to paper production) and a consequential approach (CLCA, only the processes affected by the project analyzed).

Treatment of key issues

Forest management: No land use change was considered.

Alternative use of the forest land and of the wood: No use assumption.

Sawmill co-products: For the ALCA approach, a mass allocation was applied at sawmills. For the CLCA approach, it was assumed that the decreased use of chips resulted in a reduced production in other systems.

Energy use and Energy exports/Pulping: The following was considered concerning energy use.

- Virgin and recovered fibre processing occur at the same mill.
- For the ALCA case, the Ontario power grid is affected by a change in electricity consumption/production.
- In the case of CLCA, coal power production is the marginal technology.

Recovered fibre processing rejects: Assumed to be landfilled.

Landfill emissions: The landfill process was modelled using the ecoinvent model (Doka 2003). In this model, it is assumed that 16.7% of the newspaper will degrade over 100 years. The landfill leachate for the first 100 years after deposition is assumed to be collected and treated in a municipal wastewater treatment plant.

Energy exports/End-of-life: No energy recovery was considered at end-of-life.

Recycling allocation: Three approaches were compared: 1) allocation using the cut-off method (zero burden), 2) allocation using the extraction load model, and 3) system expansion.

Substitution effects: In the CLCA approach, it was considered that 1 tonne of deinked pulp substituted for 1 tonne of TMP. Default estimates for demand and supply of price elasticity for recovered paper were used: 38% was diverted from other pulp and paper usages and had to be compensated by virgin pulp production (TMP and kraft), 62% was temporarily diverted from landfill.

Biogenic carbon: Biogenic carbon was ignored.

Data for electricity: Average for ALCA and marginal for CLCA.

Impact assessment: TRACI, LUCAS and IMPACT 2002+ were compared.

Peer review: Published in peer-reviewed literature. Study was not peer-reviewed.

Main results and conclusions: It was found that, for this case study, increasing the deinking capacity reduced most of the estimated environmental impacts disregarding the methodological choices made. This was because the TMP process consumed a significant amount of power, for which the marginal technology was assumed to be coal or natural gas.

S31. LCA EVALUATION OF ENERGY PROJECTS IN A KRAFT MILL

Document Information

Full reference: Gaudreault, C., Wising, U., Martin, G., Samson, R. and Stuart, P.R. 2008/2009. Environmental benchmarking of energy-related kraft mill modifications using LCA. *Pulp and Paper Canada* 109/12(12/1):23-30.

How to obtain: http://www.pulpandpapercanada.com/issues_PPS/story.aspx?aid=1000226708&type=Print%20Archives (accessed February 2011)

Paper grades: Office paper

Classification:

Perspective: Company

Objective: Comparison of virgin and recycled paper

Function: Production of a paper product for a certain usage

Geography: US

Summary

Objective: The objective of this study was to demonstrate the usefulness of LCA for considering changes in life cycle environmental performance due to implementation of energy-related modifications at an integrated kraft pulp and paper mill. This included substituting some of the virgin pulp with deinked pulp, which is of most interest to this review.

Functional unit: The functional unit for the LCA was 1 air-dried metric tonne (admt) of "average" product manufactured by the mill (85% paper, 12% market hardwood pulp, and 3% market softwood pulp).

Scenarios: The deinking scenarios considered in this study involved installing a 300 t/d deinking plant (DIP) at the mill. As a result of this measure, 50% of the paper would contain 30% recycled fibre, replacing the hardwood pulp fraction of virgin production.

System boundary and allocation: All on-site manufacturing processes, upstream processes, and other activities that may be affected by a change in the process operations were included, unless they led to unacceptably high levels of uncertainty.

Treatment of key issues

Alternative use of the forest land and of the wood: No use assumption.

Sawmill co-products: Mass allocation.

Energy use: With the implementation of the DIP process, it was assumed that a reduction of steam from black liquor that would have to be replaced by fossil fuels. The total electricity usage at the mill was also assumed to be increased fulfilled by the average electricity grid mix for that mill (80% coal, 20% natural gas).

Recovered fibre processing: Assumed to be landfilled.

Landfill emissions: The ecoinvent landfill process was used (Doka 2003).

Recycling allocation: System expansion was used. Recovered paper was assumed to be diverted from landfill and/or other usages. Other usages were based on actual North American statistics.

Substitution effects: It was assumed that 1 tonne of DIP displaces 1 tonne of virgin pulp.

Biogenic carbon: No accounting.

Data for electricity: Average.

Impact assessment: The TRACI method was used.

Peer review: Published in peer-reviewed literature. Study was not peer-reviewed.

Main results and conclusions: It was found that the implementation of the DIP process was marginally beneficial when it was assumed that the waste paper was diverted from the landfill and detrimental if diverted from other usages (paperboard, newsprint and tissue).

S32. LCA OF PAPER AND PACKAGING WASTE MANAGEMENT SCENARIOS IN VICTORIA

Document Information

Full reference: Grant, T., James, K.L., Lundie, S. and Sonneveld, K. 2001. *Stage 2 report for life cycle assessment for paper and packaging waste management scenarios in Victoria*. Victoria, Australia: EcoRecycle.

How to obtain: http://www.ecorecycle.vic.gov.au/resources/documents/Stage_2_Report_for_Life_Cycle_Assess_for_Packaging_Waste_Mg.pdf (accessed February 2011)

Paper grades: Newsprint, containerboard, and liquid paperboard

Classification:

- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options
- **Function:** Management of used paper product

Geography: Australia

Summary

Objective: The main objective of the LCA study was to determine the environmental savings (as far as is practical) of recycling versus landfilling, for common packaging products and old newspapers.

Functional unit: The functional unit was defined as the management of the recyclable fraction of paperboard, liquid paperboard, and old newspaper discarded at kerbside from the average Melbourne household in one week.

Scenarios: Two scenarios were investigated: recycling and landfilling.

System boundary and allocation:

Treatment of key issues

Forest management: Plantation. No land use effect analyzed.

Landfill emissions: The following was considered regarding landfills. Landfills are equipped with landfill gas capture systems. It was assumed that 55% of the gas was captured and burned for electricity. It was assumed that 50% of the non-captured gas was transformed into CO_2. Three scenarios were analyzed for the degradation of biogenic carbon in landfills. The first one assumed that the paper product would fully degrade. The second scenario assumed that 78% and 53% of the newspaper (carbon content of 43.2%) and paperboard (carbon content of 42.3%) respectively would not break down. This resulted in a sequestration of 1.24 kg and 0.824 kg of carbon dioxide equivalents. The third scenario was an intermediate one.

Recycling allocation: System expansion was used to deal with the recovery of the fibre for recycling at the end-of-life. Recovered fibre processing was included within the boundaries and the system was credited for virgin fibre production.

Substitution effects: Old newspapers were assumed to be reused in newsprint, displacing thermomechanical pulp and semi-bleached kraft pulp, and in cardboard production, displacing unbleached kraft pulp. Old corrugated containers were assumed to be reused in cardboard, displacing unbleached kraft pulp. Liquid paperboard was assumed to be reused in office paper, displacing bleached kraft pulp, in cardboard, displacing various types of chemical and mechanical pulp, and in tissue production, displacing various types of chemical and mechanical pulp.

Biogenic carbon: Stock accounting. It was assumed that carbon stocks in forests (mostly plantations) were stable.

Data for electricity: Average data (electricity production is mainly from coal).

Impact assessment: The study included indicators that were judged to be relevant for waste management: global warming, embodied energy, smog, water use, and non-degradable fraction of solid waste in landfills. Toxicity indicators were considered relevant but were excluded because of their uncertainty. Energy use was used as a proxy for acidification and eutrophication.

Peer review: A two-stage peer review process was performed. In the first stage, the data and assumptions were reviewed. The second stage consisted of a technical review of the final draft report by an independent LCA expert. A stakeholder review was also performed.

Main results and conclusions: The authors found that the most significant[15] estimated benefit of recycling was the amount of material sent to landfill. Other environmental indicators were also reduced. The benefits for the global warming indicator were observed only for the full degradation and intermediate degradation scenarios. Benefits were seen from both avoided landfill and avoided virgin production.

Note

The description of the assumptions for virgin and recovered fibre processing is available in the appendices, which are not publicly available.

S33. Environmental Assessment of Municipal Waste Management Scenarios

Document Information

Full reference:	Joint Research Center. 2007. *Environmental assessment of municipal waste management scenarios: Part I - Data collection and preliminary assessments for life cycle thinking pilot studies*. EUR 23021EN. Luxembourg: European Commission Joint Research Centre.
How to obtain:	http://lct.jrc.ec.europa.eu/pdf-directory/LCA-waste-part-I-Data-collection-and-preliminary-assessment.pdf (accessed May 2011)
Paper grades:	Cardboard and newsprint
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Management of used paper product
Geography:	Malta and Krakow (Poland)

Summary

Objective: The objective of this study was to compare different waste management alternatives.

Functional unit: The functional unit was 1 metric tonne of municipal solid waste at private households, including waste from commercial operations when this is collected together using the same infrastructure as for household waste. The results were presented per waste material fraction, in which case 1 metric tonne of the particular fraction was used as the basis for comparing the different treatment options for that fraction.

Scenarios: Five scenarios were defined, but the different waste fractions were compared based on the different technologies:

1) Home burning;
2) Controlled landfill;
3) Uncontrolled landfill;
4) Incineration; and
5) Recycling.

[15] Significance was based on normalized value using Australian data.

System boundary and allocation: The analysed product systems included collection from the household and all subsequent unit processes, but not the upstream processes generating the waste (equivalent to the reasonable assumption that the choice of waste management infrastructure does not affect the composition of the waste itself).

Alternative use of the forest land and of the wood: No use.

Sawmill co-products: Economic allocation.

Energy use: Production data from the ecoinvent database were used for virgin and recycled corrugated board and newsprint.

Corrugated board: In general, it was assumed that virgin board consumes less fossil energy than recycled board.

Newsprint: It was assumed that virgin newsprint consumes more energy (fossil and renewable) than recycled.

Energy exports/Pulping: It was assumed that more electricity was sold to the grid for recycled board than for virgin. No sold electricity was considered for newsprint. Displaced energy was assumed to be from coal.

Landfill emissions: 53% of the landfill gas was assumed to be collected and burned for electricity, displacing oil in Malta and coal in Krakow. Landfills were modelled using ecoinvent data.

Energy exports/End-of-life: It was assumed that produced electricity displaces oil in Malta and coal in Krakow.

Recycling allocation: The modelled systems included the upstream processes related to the avoided extraction and processing of virgin materials, since these were affected by the choice of waste management scenario, e.g., energy recovery versus materials recycling.

Substitution effects: 1 tonne of recycled paper product was assumed to substitute for 1 tonne of virgin paper product. Old newspapers were assumed to be reused in newsprint and old corrugated containers in corrugated containers.

Biogenic carbon: Flow accounting.

Data for electricity production: Marginal.

Impact assessment: Two midpoint methods were used: IMPACT 2002+ and EDIP 2003. Endpoints were also analyzed.

Peer review: The study was reviewed by Tomas Ekvall at IVL Swedish Environmental Research Institute Ltd., Joanna Kulczycka at Polish Academy of Sciences, Terry Coleman and Bernie Thomas at UK Environment Agency, and Paul Watkiss at Paul Watkiss Associates.

Main results and conclusions: The lowest environmental impact was observed for recycling, with incineration as the second lowest. This was observed for all paper grades and for normalized results.

S34. IMPACT OF PAPER RECYCLING ON ENERGY AND GHG

Document Information

Full reference: Laurijssen, J., Marsidi, M., Westenbroek, A., Worrell, E. and Faaij, A. 2010. Paper and biomass for energy?: The impact of paper recycling on energy and CO_2 emissions. *Resources, Conservation and Recycling* 54(12):1208-1218.

How to obtain: Purchase from www.sciencedirect.com

Paper grades: Paper and board

Classification:

- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options for paper/Virgin and recycled paper
- **Function:** Production of paper for a certain usage

Geography: Netherlands

Summary

Objective: The objective of this study was to measure the GHG and energy impact of different paper production chains from virgin, recovered, or a combination of fibres.

Scenarios: Two scenarios were analyzed. In the first one, a standard paper grade was produced from three pulp types. The energy use and GHG emissions of the three pulp types were analyzed for two system boundaries that varied with respect to the inclusion of surplus biomass. In the second one, six different paper grades were produced from pre-defined pulp types and the energy use of different paper grades for the different stages of their life-cycle was analyzed.

Functional unit: The functional unit was the weight of paper in metric tonnes.

System boundary and allocation: Cradle-to-grave system boundaries were used.

Treatment of key issues

Forest management: Sustainable forest management was assumed.

Alternative use of the forest land and of the wood: Unused wood was assumed to remain in the forest or to be available for energy production.

Energy use: Three types of pulp were modelled (kraft, thermomechanical pulping and deinking). The paper mills using kraft pulp were also considered. Fillers were excluded. Energy usage for each pulp process is illustrated in Figure B-11.

Recovered fibre processing rejects: The rejects from deinking (including plastics) were assumed to be burned for power production.

Landfill emissions: Landfill was not a disposal option in the study.

Recycling allocation: A mix of the closed-loop approximation and of system expansion (avoided burden method) was applied. It was assumed that in cases where the amount of recovered paper collected did not match the amount of recovered fibre needed for paper production, a surplus of recovered paper would reduce virgin pulp production, whereas a deficit would increase the production on virgin pulp production and hence of forest resource utilization. Note, as discussed in Section 4.3.3, this is usually done without respecting ISO 14044 additivity requirement.

Substitution effects: It was assumed that the value of recovered fibres is similar to the value of wood needed to produce the same amount of virgin fibre (via chemical pulping) when closed-loop was not used.

Biogenic carbon: No accounting.

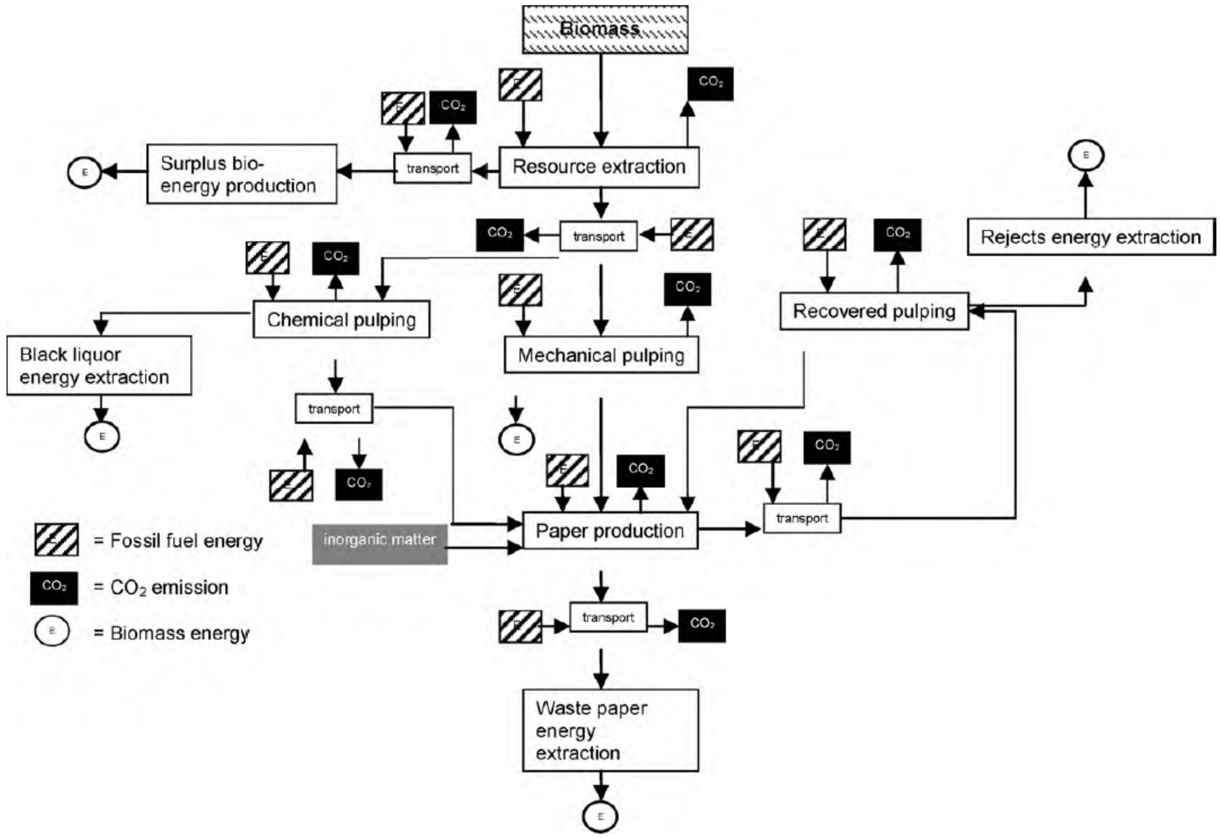

Figure B-11 Overview of Processes which Require or Produce Energy During the Paper Production Process (Laurijssen et al. 2010)

Impact assessment: Greenhouse gases and energy only.

Main results and conclusions:

No constraint of resource use: The following was observed when considering no constraint on resource use.

- Energy input is the lowest in paper from recovered pulp and highest in paper produced from chemical pulp.
- Virgin pulps have higher feedstock use, but the bio-energy produced during pulping reduces CO_2 emissions.
- The estimated CO_2 emissions are the lowest for product from chemical pulps and the highest for mechanical pulps.

With a limit on resource use: The following was observed when resource use was considered to be limited. Recycling leads to an increase in biomass available, when compared to virgin based production chains because the system boundary is expanded so the same feedstock is used for each type of pulping (i.e., surplus biomass and its usage is included in the boundary). This leads to a reduction of CO_2 emissions from mechanical and recovered pulps, and paper from recovered fibre becomes the most favourable option.

S35. LCA of Waste Paper Management: Impact of Data and System Boundary

Document Information

Full reference:	Merrild, H., Damgaard, A. and Christensen, T.H. 2008. Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. *Resources, Conservation and Recycling* 52(12):1391-1398.
How to obtain:	Purchase from www.sciencedirect.com
Paper grades:	Various grades
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Management of used paper product
Geography:	Europe

Summary

Objective: The purpose of the study was to compare waste paper recycling with incineration, with special attention to variations in environmental data.

Scenarios: Five reprocessing and eight virgin production process were modelled.

System boundary and allocation:

Treatment of key issues

Forest management: It was assumed that the effects of net carbon uptake or release in biological systems are of transient importance and thus the carbon stock for the forests is in equilibrium for the time period considered. This assumption was based on the hypothesis that the wood comes from sustainably managed forests and that carbon stocks tend to approach a new equilibrium with time.

Alternative use of the forest land and of the wood: Material not harvested for paper production was harvested for energy generation, displacing fossil fuels.

Energy exports/Pulping: Combined heat and power production from the substituted virgin biomass was included.

Energy exports/End-of-life: The energy recovery at incineration ranged from 13% of the lower heating value (LHV), a modest recovery of electricity only, to 98% of LHV, when both electricity and heat were recovered and flue gas condensation used. The marginal energy was assumed to be either natural gas or coal.

Recycling allocation: System expansion (avoided burden). Virgin paper production was assumed to be avoided when paper is recovered for recycling. Note, as discussed in Section 4.3.3, this is usually done without respecting ISO 14044 additivity requirement.

Substitution effects: The production of paper from recyclable material was assumed to substitute production from virgin material. The material quality loss was defined as the loss of quality due to the reprocessing of the paper, i.e., each time a paper fibre was recycled it lost some of its quality and new fibres had to be added in order to obtain the same paper quality. The quality loss for newspaper-quality paper was set at 0%, while for packaging paper, packaging cardboard, fine paper, and mixed quality paper, it was set at 10%.

Data for electricity: Marginal.

Biogenic carbon: Stock change accounting.

Impact assessment: Global warming only.

Peer review: Paper published in a peer-reviewed journal. No indication that the original study was peer-reviewed.

Main results and conclusions: The global warming potential was estimated to be higher for some of the virgin pulping processes than for recovered fibre processing, and lower for some others. The authors concluded that as the net impact of paper recycling is dependent on the combination of processes, a study can give very different results depending on the choice of data sources. The energy mix used for virgin paper production can greatly influence results. The choice of recycling technology and the conclusion as to whether recycling or incineration is most environmentally beneficial are strongly linked.

S36. GHG IMPLICATIONS OF INCREASING THE RECOVERY RATE FOR MILK ASEPTIC PACKAGING

Document Information

Full reference: Mourad, A.L., Garcia, E.E.C., Vilela, G.B. and Von Zuben, F. 2008. Influence of recycling rate increase of aseptic carton for long-life milk on GWP reduction. *Resources, Conservation and Recycling* 52(4):678-689.

How to obtain: Purchase from www.sciencedirect.com

Paper grades: Aseptic packaging

Classification:

- **Perspective:** Company
- **Objective:** Comparison of end-of-life options
- **Function:** Production of a paper product for a certain usage

Geography: Brazil

Summary

Objective: The objective of this study was to apply LCA to measure the global warming potential that results from the reduction of greenhouse gas emissions associated with recycling rates of 2%, 22%, 30%, 40%, and 70% of Tetra Pak Aseptic post-consumer packaging material waste.

Functional unit: The functional unit was defined as 1000 litres of milk filled in aseptic packages with a holding capacity of 1 litre each, in order to measure the GWP and estimate the impact of the efforts of Tetra Pak to stimulate selective waste collection and recycling of post-consumer packages.

System boundary and allocation: A cradle-to-grave system boundary was used. The study did not include milk production or the production of the inputs used in the manufacturing of the packaging materials, such as caustic soda, sodium sulphate, aluminum sulphate, kaolin, and starch.

Treatment of key issues

Forest management: Land use was accounted for on a surface basis.

Alternative use of the forest land and of the wood: No use.

Energy use: In Brazil, electricity is produced mainly from hydropower. Kraft mills were considered to be self-sufficient.

Landfill emissions: It was assumed that unrecovered fibre was landfilled and that all carbon is degraded to methane and CO_2 (50%, 50% on a molar basis).

Recycling allocation: The study used a cut-off approach.

Substitution effects: Recovered material was assumed to be reused in the production of boxes.

Biogenic carbon: No accounting.

Data for electricity: Average.

Impact assessment: Global warming and energy only.

Peer review: Published in a peer-reviewed journal. No mention that the study has been peer-reviewed.

Main results and conclusions: The results showed significant reduction of the energy requirements and global warming when increasing the recovery rate.

S37. Waste Management Options to Reduce GHG in Australia

Document Information

Full reference: Pickin, J.G., Yuen, S.T.S. and Hennings, H. 2002. Waste management options to reduce greenhouse gas emissions from paper in Australia. *Atmospheric Environment* 36(4):741-752.

How to obtain: Purchase from www.sciencedirect.com

Paper grades: General

Classification:

- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options
- **Function:** Production of a paper product for a certain usage

Geography: Australia

Summary

Objective: The objectives of this study were to provide a comprehensive investigation of total GHGs from the paper cycle in Australia, from forest to landfill, and to assess the effectiveness of various waste management options to reduce GHGs from paper.

Functional unit: The functional unit was defined as 1 tonne of paper.

Scenarios: Three options were simulated:

- paper recycling;
- waste-to-energy; and
- various adjuncts (landfill gas recovery, composting and waste-to-energy) to paper recycling.

System boundary and allocation:

Treatment of key issues

Landfill emissions: The emissions from the decay of landfilled waste paper were estimated on the basis of historical production data and an assumed exponential decay rate. It was assumed that 77% of the degradable organic carbon (DOC) in landfilled organic material will be gasified if lignin-based carbon is not counted as DOC. The DOC component was estimated by subtracting the lignin-based carbon content from the average carbon content of paper. A half-life of five years was assumed. Anaerobic degradation of paper was assumed to produce CH_4 to CO_2 in the proportion of 1:1. It was assumed that any energy recovered from waste paper is converted to electricity at an efficiency rate equal to the average for electricity generation in Australia. Avoided emissions were calculated. Five percent of consumed paper was assumed to enter net storage.

Energy exports/End-of-life: In this study, it was assumed that any energy recovered from waste paper is converted to electricity at an efficiency rate equal to the average for electricity generation in Australia. Avoided emissions were calculated.

Recycling allocation: System expansion.

Biogenic carbon: Flow accounting.

Impact assessment: GHGs only.

Date: Average.

Peer review: Published in peer-reviewed literature.

Main results and conclusions: The authors found that recycling significantly decreased GHG emissions but that waste-to-energy provided more benefits.

S38. LCA OF VARIOUS DISTRIBUTION SYSTEMS

Document Information

Full reference: Ryberg, A., Ekvall, T. and Person, L. 2000. *Life Cycle Assessment of distribution in four different distribution systems in Europe*. Stockholm: CIT Ecologik, Chalmers Industriteknik.
How to obtain: http://tinyurl.com/3romu79 (Executive Summary accessed May 2011)
Paper grades: Unbleached and bleached sack paper
Classification:
Perspective: Societal
Objective: Comparison of end-of-life options
Function: Production of a paper product for a certain usage
Geography: Europe

Summary

Objective: Eurosac and CEPI Eurokraft chose to use LCA to assess the environmental performance of paper sacks and to compare them with other sacks.

Functional unit: The functional unit chosen for the systems compared in this study was *the distribution of 1000 kg of filling goods to the customers*.

Scenarios: For the paper sacks four end-of-life scenarios were analyzed:

- 100% recycling;
- 100% incineration with energy recovery;
- 100% landfilling; and
- 100% composting.

System boundary and allocation:

Treatment of key issues

Alternative use of the forest land and of the wood: No use.

Sawmill co-products: Mass allocation.

Energy use: Based on (FEFCO 1997).

Energy exports/Pulping: Based on (FEFCO 1997).

Recovered fibre processing rejects: Based on (FEFCO 1997).

Landfill emissions: It was assumed that 20% of the methane emitted from the landfill sites is collected as biogas and used for energy production.

Energy exports/End-of-life: It was assumed that 75% of the produced heat and electricity is heat and that the remaining 25% is electricity, that the efficiency for waste-based heat production is 80% and that the efficiency for waste-based electricity production is 22%. The heat produced in waste incineration was assumed to replace district heat produced from other fuels (60% light fuel oil and 40% natural gas).

Recycling allocation and Substitution effects: The system boundary was expanded to include parts of other life cycles that are affected by recovering the fibre for recycling. It was assumed that a material, which is collected for recycling after use, enters a market where it competes with virgin material as well as recycled material from other systems. It was assumed that recovered paper sacks were used for the production of testliner. The testliner produced from recovered fibres was assumed to be sold on the liner market where it would replace a mix of kraftliner (44%) and testliner (56%).

Biogenic carbon: No accounting.

Data for electricity: Average.

Impact assessment: The following impact categories were included: abiotic resource depletion, global warming, acidification, nutrient enrichment, photochemical ozone formation, aquatic ecotoxicity, human toxicity. Toxicity indicators were not used for the comparisons. Use of primary energy was also analyzed.

Peer review: An external independent expert (Dr. Jeroen Guinée, CML, Netherlands) was selected by the commissioner of the study to perform the critical review. However, due to a delay in the study, Dr. Guinée was unable to finish the critical review. Instead, Ester van der Voet (also CML) took over after the first review round and performed rounds two and three.

Main results and conclusions: For most categories, incineration was estimated to have lower environmental impacts than recycling because the energy produced at the incineration has been assumed to replace heat and electricity from other fossil fuels and the recycled material has been assumed to replace not only virgin material, but a mix of virgin and recycled material. The landfill scenario was estimated to have the highest potential contribution to global warming. This was due to the methane emitted when the paper is degraded at landfilling. When assuming that the recycled material from the sack system replaces 100% virgin material, the observed contributions from the recycling scenarios to the studied impact categories decreased significantly.

S39. DANISH WASTE HIERARCHY FOR PAPER

Document Information

Full reference: Schmidt, J.H., Holm, P., Merrild, A. and Christensen, P. 2007. Life cycle assessment of the waste hierarchy - A Danish case study on waste paper. *Waste Management* 27(11):1519-1530.

How to obtain: Purchase from www.sciencedirect.com

Paper grades: Entire paper production system (31% corrugated paper and paper bags, 23% newspaper, 20% coated paper, 15% cardboard, and 12% uncoated wood-free paper)

Classification:

- **Perspective:** Societal
- **Objective:** Comparison of end-of-life options/Virgin and recycled paper
- **Function:** Production of a paper product for a certain usage

Geography: Denmark

Summary

Objective: The objective of this study was to perform an LCA of the total Danish waste paper stream, including different scenarios for handling this stream and to propose different strategies relating to recycling, incineration and landfill in order to experience the overall environmental effects of the changes.

Functional unit: The functional unit was defined as Denmark's consumption of paper in 1999 [1.2 million tons (1.122 million tons dry solids)]. See Figure B-12.

Scenarios: Three scenarios were defined.

- Reference situation in Denmark in 1999
- Scenario 1: moving paper from incineration to recycling
- Scenario 2: terminating the collection scheme for paper in Denmark, moving paper from recycling to incineration causing a significant increase in demands for virgin pulp
- Scenario 3: closing down incineration plants in Denmark and disposing waste in landfills instead, while at the same time maintaining the same level of recycling as in 1999

System boundary and allocation: All life cycle stages of paper were included, from forestry to final disposal of waste paper.

Treatment of key issues

Forest management its alternative use: It was assumed that roundwood consumption was constant between scenarios. A decreased usage of virgin pulp would result in an increase energy production from roundwood, which would substitute some of the electricity and heat produced at a CHP plant (as cogeneration of heat and electricity, which is today state-of-the-art in Denmark).

Energy use and energy exports/Pulping: Most Danish production of pulp and paper was considered in the analysis. The following was also considered. Generally, CHP plants are sized so that they are able to cover the need for heat in the paper production. The produced electricity is used in the production and eventually, any surplus would be sold to the grid in the same way as a deficit in electricity production would be compensated for by buying it from the grid. Virgin paper used in Denmark is produced primarily in Sweden, Finland, and Germany, while recycled paper is produced locally. However, it was assumed that increased usage of recovered fibre would occur in foreign markets. It was assumed that energy requirements for the production of virgin pulp and paper were met by 69% wood residuals, 20% natural gas, 8% oil and 3% coal, while fuel consumption in production of recovered pulp was met by natural gas. Based on European best available techniques (European Commission 2001), it was assumed that that the total energy requirements for the production of 1 tonne of virgin paper (from 61% chemical, 10% semi-chemical, and 29% mechanical pulp) are 21.8 GJ; while the corresponding energy requirements for the production of 1 tonne of paper from recovered pulps are 9.6 GJ.

Recovered fibre processing rejects: It was assumed that deinking wastes are incinerated but without any concomitant production of energy, as the water content of this fraction is fairly high.

Landfill emissions: Landfilling was based on the Buwal database, which does not include any biogenic carbon dioxide. Only the controlled phase of the landfill was included in this database, which indicates a partial degradation of the carbon.

Energy exports/End-of-life: The following was assumed. Paper waste not collected for recycling would end up in mixed waste for incineration. The production of energy displaces marginal electricity and heat. Danish waste incineration plants have total energy efficiency of 85%, distributed as 24% electricity and 61% heat.

Recycling allocation: The system boundary was expanded to include the whole Danish paper production and recycling occurs within this system. Hence, no allocation was required.

Substitution effects: It was assumed that every time waste paper undergoes the process of recycling, its fibres are worn down (“down-cycled”). Thus, it is only possible to recycle the fibres 4–6 times. For this reason, it is always necessary to add virgin pulp to keep the total stock of paper.

Biogenic carbon: No accounting.

Data for electricity: Marginal (natural gas).

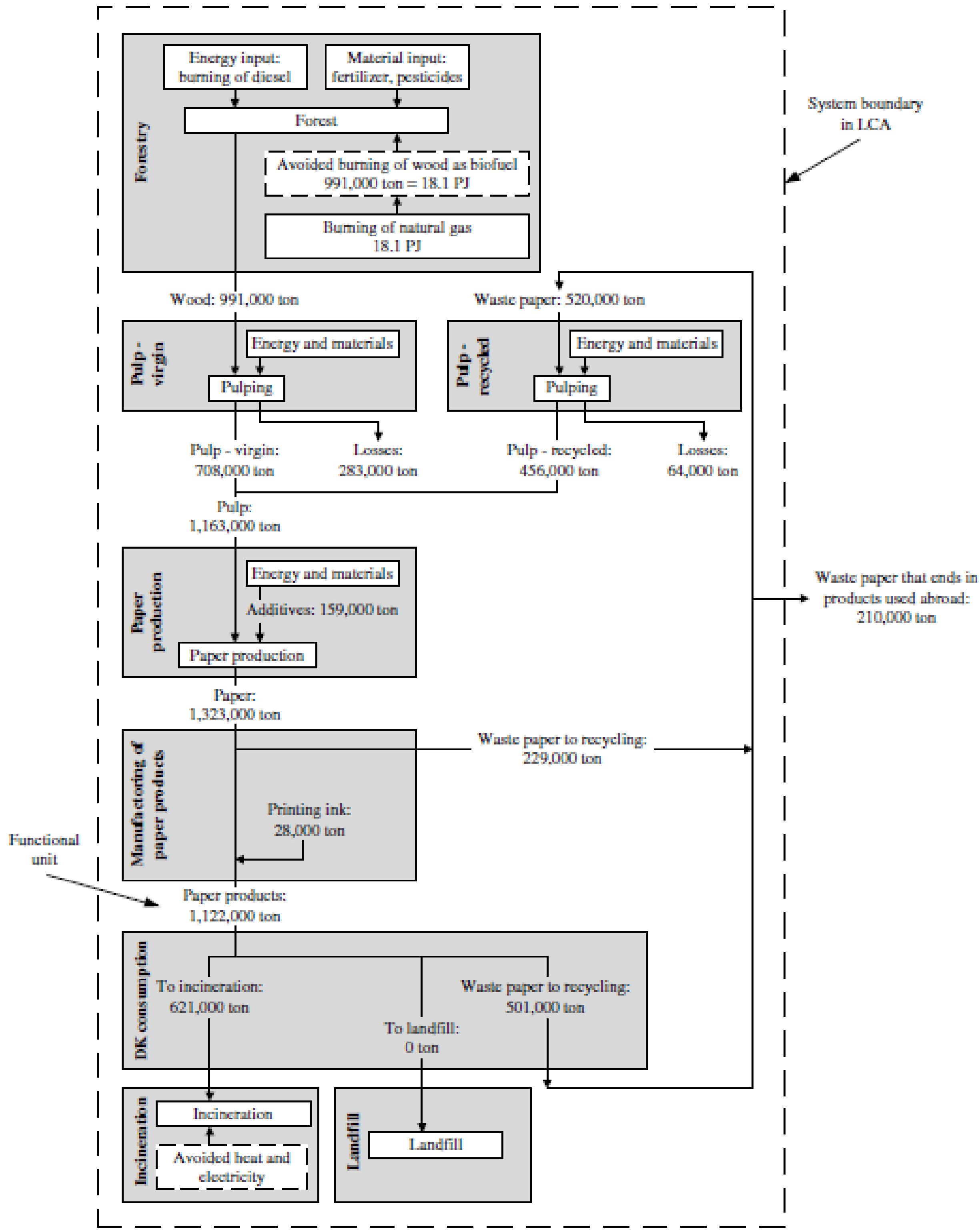

Figure B-12 Paper Flows in Denmark (Schmidt et al. 2007)

Impact assessment: The EDIP97 method was applied. Only the following impact categories were included: global warming, ozone depletion, eutrophication, acidification, and photochemical smog. Normalization based on emissions per capita was included.

Peer review: This paper is published in the peer-reviewed literature.

Main results and conclusions: Using the normalized results, the authors found that the most significant impacts from handling paper in the 1999 situation were 1) global warming, 2) acidification, and 3) eutrophication. The recycling scenario was found to produce the lowest results for the global warming and acidification indicators, while the incineration scenario was found to produce the second lowest results. Incineration was found to produce slightly lower results for the eutrophication and smog indicators. The main reason increased recycling produced lower results compared to incineration for the global warming and acidification indicators was that the indirect effects of using wood have been taken into account. Depositing waste paper in landfills produced highest results for all impact categories.

S40. LCA OF GRAPHIC PAPERS

Document Information

Full reference:	Tiedemann, A. 2001. *Life cycle assessments for graphic papers*. Nr 2/2001, Umweltbundesamt. Berlin: German Federal Environmental Agency.
How to obtain:	http://www.umweltdaten.de/publikationen/fpdf-l/1925.pdf (accessed February 2011)
Paper grades:	Graphic paper
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Production of a paper product for a certain usage
Geography:	Germany

Summary

Objective: The main objectives of this study were to rank recycling and incineration and to compare recovered paper and wood as raw material for fibre production according to their life cycle environmental performance.

Functional unit: The functional unit was set to be the total consumption of graphic papers in Germany in 1995. A constant amount of energy production was also added to the functional unit to ensure all compared systems were equivalent.

Scenarios: A reference scenario was defined as having a recovery rate of 69%. Low (57%) and high (76%) recovery rate scenarios were also defined. Sensitivity analyses were performed by varying the proportion of unrecovered paper to landfill, domestic and municipal incineration, the origin of wood, the fate of surplus wood, and the substitution assumptions for energy processes.

System boundary and allocation: The system boundary was set from cradle-to-grave, as illustrated in Figure B-13.

Treatment of key issues

Forest management and alternative use: Use of forest land was analyzed by defining different land quality and investigating the effect of recycling. Wood surplus was assumed to remain in the forest or to be used for energy generation.

Landfill emissions: It was assumed that the entire quantity of organic carbon in the paper is degraded to gas (19% methane, 81% carbon dioxide).

Energy exports: Substituted heat was produced from coal and natural gas and electricity from the average German power mix.

Recycling allocation: System expansion was used.

Biogenic carbon: No accounting of biogenic CO_2.

Data for electricity: Average.

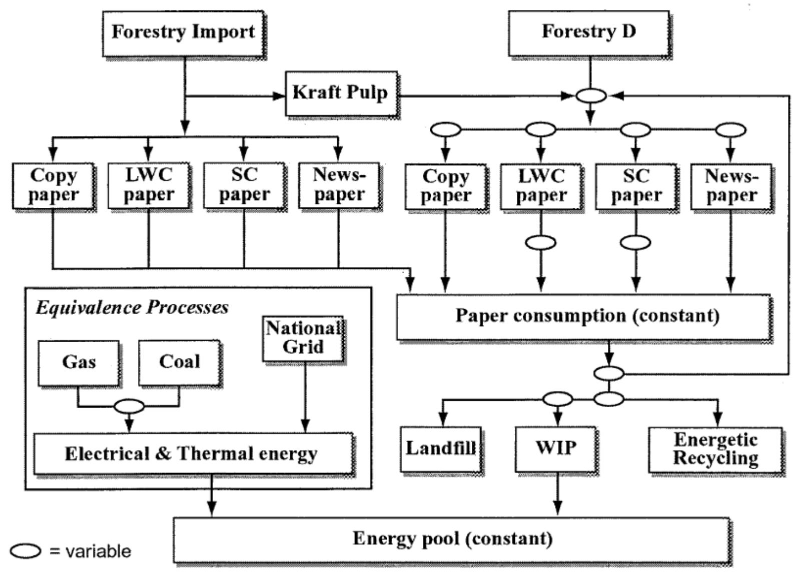

Figure B-13 System Boundary for the LCA of German Graphic Papers (Tiedemann 2001)

Impact assessment: The impact categories included were terrestrial eutrophication, acidification, greenhouse gases, aquatic eutrophication, ground level ozone formation, direct harm to health, direct harm to ecosystems, use of natural areas, scarcity of fossil fuels, and water consumption. Harm to health and ecosystem was analyzed through the emission of specific substances.

Peer review: The study was peer-reviewed by three experts.

Main results and conclusions: The study concluded that

- increasing the recovery rate has significant benefits for most impact categories but results in an increased emission of lead;
- burning waste paper is preferable when the energy is recovered, but always preferable in comparison to landfilling;
- incineration with energy recovery was found to produce lower indicator results only in the case where coal energy is substituted; and
- the higher the recovered fibre content, the better the environmental performance of paper.

S41. US LCA OF SOLID WASTE MANAGEMENT

Document Information

Full reference:	United States Environmental Protection Agency (USEPA). 2006. *Solid waste management and greenhouse gases – A life cycle assessment of emissions and sinks,* 3rd ed. EPA530-R-06-004. Washington, DC: United States Environmental Protection Agency.
How to obtain:	http://www.epa.gov/climatechange/wycd/waste/downloads/fullreport.pdf (accessed February 2011)
Paper grades:	Corrugated cardboard, newspaper, office paper, magazines and third-class mail, phonebooks, textbooks
Classification:	
Perspective:	Societal
Objective:	Comparison of end-of-life options
Function:	Management of used paper product
Geography:	US

Summary

Objective: The objective of this report was to calculate the life cycle emissions and sinks of GHGs for various waste management alternatives.

Functional unit: All calculations were based on 1 short ton of paper.

System boundary and allocation:

Treatment of key issues:

Forest management and alternative use and Biogenic carbon: The stock change approach was used. Carbon storage was included, to the extent that it was due to waste management practices. It was also assumed that harvesting trees at current levels would result in no decrease in the forest carbon stock and no additional CO_2 to the atmosphere. On the other hand, it was assumed that forest carbon sequestration increased as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling "got credit" for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) did not. This is equivalent to the "no use" assumption for the alternative usage of the forest area. Only the actual reduction in pulpwood was considered. EPA found that increased recycling of paper products resulted in incremental forest carbon storage of about 2.01 tonnes CO_2 per ton of paper recovered for mechanical pulp papers and 3.04 tonnes CO_2 per ton of paper recovered for chemical pulp papers.

Energy use and Energy exports/Pulping: Energy consumption was modelled to be higher for recycled corrugated and office paper than for virgin. For production of other products, energy consumption was modelled to be either the same, or the production of recycled products was modelled to consume less energy than virgin products.

Landfill emissions: Carbon stored in landfills was estimated based on experiments. The following assumptions were made to calculate the quantity of methane emitted from landfills.

- Non-stored carbon is transformed into a biogas containing equal volumes of CH_4 and CO_2.
- 10% of the landfill CH_4 generated that is not recovered in a collection system is either chemically oxidized or converted by bacteria to CO_2.

- Landfills that recover landfill gas (LFG) have an efficiency of 75%.
- 59% of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 41% was generated at landfills without LFG recovery.
- Of the 59% of all CH_4 generated at landfills with LFG recovery, 53% (or 31% of all CH_4) was generated at landfills that use LFG to generate electricity, and 47% (or 28% of all CH_4) at landfills that flare LFG.

Energy exports/End-of-life: Waste that is used to generate electricity (either through waste combustion or recovery of CH_4 from landfills) was assumed to displace fossil fuels that utilities would otherwise be used to produce electricity.

Recycling allocation: Closed-loop was used except for mixed papers (system expansion).

Substitution effects: It was assumed the recycled material is used in place of virgin material of the same type.

Impact assessment: Greenhouse gases only.

Data: Average.

Main results and conclusions: In almost all cases, recycling was found to produce the lowest estimated GHG emissions. The benefits of recycling were attributable to avoided landfill methane and increased stocks of carbon in the forest. Landfilling was found to be the option with the highest GHG emissions for all products except for newspapers and phone books, which produced lower emissions from landfilling than from incineration because of carbon storage in landfills.

Notes

Results from this study are used in EPA's Waste Reduction Model (WARM) and in its Recycled Content Tool (ReCon).The full report for this study was last published in 2006. In 2010, new data and documentation were published (http://epa.gov/climatechange/wycd/waste/SWMGHGreport.html).

The changes that were made in the 2010 version that could have an effect on the results as discussed previously are

- incorporation of new data on landfill methane generation distribution and landfill gas recovery and flaring rates;
- revision of the waste-to-energy combustion pathway energy values to consider the ratio of mass burn combustion facilities (17.8%) and the national average electric utility grid combustion efficiency (32%); and
- modification of the recycling emission factors for the mixed paper material types to include updated recycled boxboard data.

The general conclusions for paper products are similar to those obtained in 2006, with one exception. Magazines and third-class mail are now added to the list for which landfill produces less GHG emissions than waste-to-energy (slightly less).

B.4 OTHERS

In this section, a critical review of the *Lifecycle Environmental Comparison: Virgin Paper and Recycled Paper-Based Systems* study (Environmental Defense Fund 2002) is presented. This study has been excluded from the list of studies reviewed in this Technical Bulletin because it does not follow the ISO 14040 requirements. However, it is widely cited and was the background study for the Paper Calculator 1.0. The background information for Paper Calculator 3.0 (http://www.edf.org/papercalculator/) is not yet available.

Document Information

Full reference:	Environmental Defense Fund. 2002. *Lifecycle environmental comparison: Virgin paper and recycled paper-based systems*. New York: Paper Task Force.
How to obtain:	http://www.edf.org/documents/1618_WP3.pdf (accessed February 2011)
Paper grades:	Newsprint, corrugated board, office paper, paperboard
Classification:	
Perspective:	Societal
Objective:	Both
Function:	Both
Geography:	US

Summary

Objective: This paper summarized the research and findings of the Paper Task Force on the environmental impacts associated with paper recycling in comparison with managing paper through the major means of solid waste management. Two approaches were applied in this study: one where the studied product is the waste, and one where the studied product is the paper.

Functional unit: 1 ton of paper.

Scenarios: Landfilling, incineration (with energy recovery), and recycling were compared.

System boundary and allocation: In the first version of the study, the system boundary was defined as starting with the recovery or discarding of potentially recyclable paper-based materials in municipal solid waste (MSW) and following the materials to the point where they are either 1) disposed of in a landfill; 2) burned in an MSW incinerator and the resulting ash residue is disposed of in a landfill; or 3) processed and transported back to the site of remanufacture. Then, the full life cycle of paper was assessed by considering the following three alternative complete systems:

1) acquisition of virgin fibre, manufacture of virgin paper, followed by landfilling;
2) acquisition of virgin fibre, manufacture of virgin paper, followed by incineration; and
3) manufacture of recycled paper, followed by recycling collection, processing and transport to the site of remanufacture.

This method is somewhat uncommon.

In general, in the reviewed literature, if the studied system is the waste or if the studied system is the paper and the objective is to compare different waste management options for this paper, then the boundary is expanded to include the avoided virgin production due to recycling. On the other hand, in cases where the objective is to compare virgin paper with recycled paper, the ***cut-off*** *or the* ***number of subsequent uses methods*** *have been used.*

*The method used in the EDF study is referred in the literature as the "****extraction-load****" model. The rationale for this method is that, since all material will ultimately end up as a waste, final waste management is an inevitable consequence of material extraction from the environment (Ekvall and Tillman 1997). This method promotes the use of recovered material in cases where the environmental load of recycling is less than the combined environmental load of virgin production and final waste management. This is almost always the case for paper products. In contrast, it is also possible to find in the literature a method that assigns the virgin production and end-of-life loads to the system in which the product is disposed of. This method is referred to as the "****disposal-load****" model. The rationale is that, to avoid reductions in the material available for human use, material lost must be replaced with virgin material. This method promotes recycling in cases where the environmental load of recycling is less than the combined environmental load of virgin production and final waste management.*

The ISO 14044 standard is not rigid concerning which method to use for open-loop recycling allocation (i.e., uses "should" and not "shall"). However, it does not specifically mention either the extraction-load or cut-off method. On the other hand, it requires that "whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach"(ISO 2006b, 14). The Environmental Defense Fund study did not assess the effect of the choice of allocation procedure for recycling on the results. The use of the "number of subsequent uses" method, which is mentioned in the ISO standard, may have significantly affected the results obtained.

<u>Treatment of key issues</u>

Forest management and its alternative use: Forest activities were included. The implicit choice made when selecting the allocation procedure for recycling is that if the wood is not harvested for virgin pulping then it will remain in the forest.

Energy use and Energy exports/Pulping: Virgin and recycled fibre processing were modelled as follows. Virgin chemical pulp mills generate a substantial portion of their energy needs by burning wood residues (e.g., bark) and pulping liquors, thereby reducing their use of fossil fuels. Recycled pulp mills do not generate such fuel sources, and therefore generally must purchase their energy in the form of fossil fuels or electricity generated largely from fossil fuels (or both). That said, such mills also avoid the purchased energy (in the form of fuels) required by virgin mills to grow and harvest trees and transport logs to the mill. The relative amounts of purchased vs. self-generated energy vary with not only recycled vs. virgin pulp, but also with paper grade, the specific mill or company involved, and geographic location.

Landfill emissions: The following assumptions were made.

- 123.0 pounds of methane is produced per ton of waste landfilled.
- A typical recovery rate for methane from landfill gas is 66%.
- A typical gas turbine can generate 1.75 kilowatt-hours (kWh) of electricity per pound of methane burned, based on an energy value of landfill gas (methane) of about 500 Btu per cubic foot of gas.

- 144 kWh of electricity could be produced per ton of waste landfilled, the fossil-fuel equivalent of 1,542,500 Btus per ton.

Energy exports/End-of-life: Energy production at landfills and incineration was included through system expansion.

Recycling allocation: See above.

Substitution effects: It was assumed that old newspapers are recycled in newsprint, office paper waste is recycled in office paper, old corrugated containers are recycled in corrugated board and old paperboard is recycled in paperboard.

Note that in reality, this closed-loop assumption can be considered to be accurate only for corrugated containers (AF&PA 2007).

Biogenic carbon: No accounting of biogenic carbon dioxide.

Data for electricity: Average.

Impact assessment: No impact assessment was performed. Instead, the following indicators were evaluated: solid waste output, energy use, air emissions, and waterborne wastes.

Peer review: On August 10, 1994, the Task Force assembled a panel of experts from several sectors to discuss environmental impacts associated with recycling in comparison with solid waste management. Panellists discussed an issue paper that had been prepared by the Task Force, which laid out the relevant environmental issues surrounding recycling and waste management methods, as well as the range of perspectives and opinion on those issues held by various stakeholders. The issue paper was also reviewed by several other outside experts. The panellists' and reviewers' comments on the issue paper were considered in drafting the report for that study, which was also reviewed by a range of experts.

Main results and conclusions:

Solid waste: Virgin production plus incineration (with energy recovery) for newsprint, corrugated containers, office paper and coated unbleached kraft (CUK) paperboard resulted in the least solid waste of the three options, slightly less than recycled production plus recycling and considerably less than virgin production plus landfilling.

Total energy use: Recycled production plus recycling for newsprint, corrugated containers, office paper, and paperboard used the least total energy of the three options. Virgin production plus landfilling used the most total energy.

Purchased and fossil fuel energy use: Recycled production plus recycling for newsprint used the least purchased and fossil fuel-derived energy of the three options, while for the other grades, virgin production plus incineration used the least purchased and fossil fuel-derived energy. Virgin production plus landfilling of newsprint and solid bleached sulphate (SBS) paperboard used the most purchased and fossil fuel-derived energy of the three options, while recycled production plus recycling of the other three grades used the most purchased and fossil fuel derived energy.

Air emissions:

- Newsprint: Of the three options, recycled production plus recycling produced the lowest estimated emissions of net GHGs, nitrogen oxides, particulates, and sulphur oxides. Virgin production plus landfilling produced the highest estimated emissions in all of these categories, while virgin production plus incineration yielded intermediate levels of emissions. Virgin production plus landfilling was found to have the highest environmental impact.
- Corrugated board: Virgin production plus incineration was found to produce the lowest estimated emissions of net GHGs and sulphur oxides. For nitrogen oxides and particulates, the two options were found to produce comparable estimated emissions. Virgin production plus landfilling was found to produce the most emissions.

- Office paper: Recycled production plus recycling was found to produce the lowest estimated emissions of nitrogen oxides and particulates, while virgin production plus incineration produced the lowest estimated emissions of net GHGs and sulphur oxides. Virgin production plus landfilling was found to produce the most emissions.
- CUK paperboard: Virgin production plus incineration was found to produce the lowest estimated emissions of net GHGs and sulphur oxides. For nitrogen oxides and particulates, the estimated emissions of the two options were comparable. Virgin production plus landfilling was found to produce the most emissions except for sulphur oxides.
- Solid bleached sulphate paperboard: Recycled production plus recycling was found to produce the lowest estimated emissions of nitrogen oxides and particulates. For net GHGs, virgin production plus incineration was found to produce the lowest estimated emissions, while for sulphur oxides, the two options were found to produce comparable estimated emissions. Virgin production plus landfilling was found to produce the most emissions.
- For all three grades of paper, recycled paper manufacturing produced lower estimated emissions of HAPs, VOCs and TRS than did virgin fibre-based manufacturing. This conclusion was based on a gate-to-gate evaluation of the manufacturing processes.

- Water releases:
  - Newsprint: Recycled production plus recycling produced the lowest estimated releases of chemical oxygen demand (COD), but the highest estimated releases of biochemical oxygen demand (BOD) and suspended solids, of the three options.
  - Corrugated board: Recycled production plus recycling produced the lowest estimated releases of COD and suspended solids, and comparable estimated releases of BOD compared to the other two options.
  - Office paper: Recycled production plus recycling produced the lowest estimated releases of COD and suspended solids. With respect to BOD, there was no significant difference among the three options.
  - Paperboard: Recycled production plus recycling produced the lowest estimated releases of the three options in all of these categories.
  - In contrast to virgin manufacturing processes for office paper and SBS paperboard that utilize chlorinated compounds (elemental chlorine and/or chlorine dioxide) for bleaching, the use of recovered fibre in manufacturing office paper or paperboard was expected to generate no discharge of AOX. This conclusion was based on a gate-to-gate evaluation of the manufacturing processes.
  - The recycled manufacturing process resulted in less (or for newsprint, comparable) estimated effluent discharge compared to the virgin manufacturing process. This conclusion was based on a gate-to-gate evaluation of the manufacturing processes.
- Wood use: The recycled manufacturing process consumed no wood in the form of trees. The virgin manufacturing processes consumed between about 2 tons (for newsprint) to 3.8 tons (for SBS paperboard) of wood in the form of trees, per ton of final product.

Notes on Paper Calculator 1.0

In summary, the approach taken in this study, though different, is consistent with the approaches taken in other studies comparing different waste management options for paper. For this reason, the conclusions obtained can be considered as valid as others in regards to the estimated environmental superiority of waste management options. However, the results are used to compare virgin paper with recycled paper, which is an overextension of the applicability of this tool beyond its functional capability. The information provided in the report is not sufficient to make conclusions on this comparison. Further analyses (e.g., sensitivity analysis on the allocation procedure and assessment of the sustainability of the fibre cycle) would have been very useful in this context.

Some notes on Paper Calculator 3.0

NCASI has examined the draft documentation for Paper Calculator 3.0, provided by Kim Porter of Environmental Paper Network on March 18, 2011. In terms of changes compared to the previous version, the open-loop recycling approach has been modified. From the draft documentation, it would appear that in the new version of the calculator, the virgin fibre is given landfill-related burdens only to the extent that product is landfilled. Products containing recycled fibre also receive landfill-related burdens reflecting the fraction of product that is landfilled, but they also receive a credit for avoiding the landfilling of recovered fibre used in the product. This credit is derived using an assumption that when a ton of recovered fibre is used, 2/3 tons of paper is not landfilled (based on assumptions about the fibre being used three times in total). It is difficult to know exactly how this new approach affects the comparison of virgin and recovered fibre. Several things are clear, however.

- This approach almost certainly is less disadvantageous to virgin fibre than the earlier method.
- This approach is still quite favourable to recovered fibre compared to an approach wherein loads are shared throughout the life cycle based on the number of uses (instead of only crediting recycled fibre with avoided emissions based on the number of uses).
- The ISO 14044 standard requires that *"allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration"* (ISO 2006b, 14). The new version of Paper Calculator does not achieve that requirement, since a system expansion approach is used for the use of recovered fibre, and a cut-off method for end-of-life recovery. The inconsistencies in this approach are acknowledged in the documentation, which states, "Limitations in the structure of the Paper Calculator do not allow the methodology to be applied consistently over all aspects of the life cycle; the method is used only for solid waste and the associated energy recovery and greenhouse gas emissions from decomposition."
- As with earlier versions of the Paper Calculator, the impacts of using more or less recovered fibre are determined by moving up and down a straight line that connects the points describing the performance of "virgin" and "recycled" materials.

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