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METHODS FOR OPEN-LOOP RECYCLING ALLOCATION IN LIFE CYCLE ASSESSMENT AND CARBON FOOTPRINT STUDIES OF PAPER PRODUCTS

TECHNICAL BULLETIN NO. 1003
DECEMBER 2012

by
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PRESIDENT'S NOTE

For many years, the industry has been responding to questions from customers and other important stakeholders about the environmental implications of paper recovery and recycling. There are many ways to approach these questions, but increasingly, they are being examined using life cycle assessment (LCA), which is the study of the potential environmental and resource impacts of a system from cradle-to-grave.

While LCA studies, and closely related carbon footprint studies, provide a useful structure for understanding the implications of fiber recovery and recycling, the application of LCA to these questions is not straightforward. In part, this is because there are many situations in which wood fiber is used to produce one type of product, after which it is then recovered and used to make a different type of product. An example of this type of recycling, which is called "open-loop" recycling by LCA practitioners, is the use of recovered office paper to produce recycled tissue paper. When performing an LCA on a system producing recycled tissue paper, one must therefore decide how to "allocate" various environmental loads and resource requirements between two connected systems, one of which produces the recovered fiber (the office paper system) and the other that uses it as a raw material (the tissue paper system).

In this report, several open-loop recycling allocation methods are explained, examined, and illustrated. The reader should be aware that the International Organization for Standardization (ISO) has issued standards and guidance addressing many of the issues discussed in this report. Companies interested in the allocation questions that arise in LCA and carbon footprint studies should familiarize themselves with this ISO material, much of which is summarized in this report. A body of literature and practice related to the ISO standards and guidance has emerged over time. Because companies may encounter this supplemental material, some of it is reviewed herein. This supplemental material, however, lacks the international expert consensus and global standing attached to ISO standards and guidance, and companies should be mindful of this limitation.

The report highlights the potential for the results of an LCA to be greatly influenced by the selection of an allocation method. This report is a partner to Technical Bulletin No. 1002, which discusses co-product allocation methods, and does not limit any of the options available to companies under ISO standards and guidance. Companies are responsible for selecting and justifying the methods used for allocation in studies they perform and for any claims based on those studies.

Ronald A. Yeske

December 2012

NOTE DU PRÉSIDENT

Depuis de nombreuses années, l'industrie répond aux questions de ses clients et d'autres intervenants importants sur les conséquences environnementales de la récupération et du recyclage du papier. Il y a plusieurs façons d'aborder ces questions, mais de plus en plus, elles sont abordées à l'aide d'analyses du cycle de vie (ACV). L'ACV est l'étude des impacts potentiels d'un système sur l'environnement et les ressources, du berceau au tombeau (cradle-to-grave).

Bien que les études ACV, et aussi les études de l'empreinte carbone qui y sont étroitement liées, fournissent une structure utile pour comprendre les implications environnementales de la récupération et du recyclage de la fibre, l'application de l'ACV à ces questions n'est pas simple. Cette complexité est en partie due au fait qu'il existe de nombreuses situations dans lesquelles la fibre de bois est utilisée pour fabriquer un type de produit, après quoi elle est ensuite récupérée et utilisée pour fabriquer un autre type de produit. Un exemple de ce type de recyclage, qui est appelé recyclage en «circuit ouvert» ou en «boucle ouverte» par les praticiens de l'ACV, est l'utilisation de papier de bureau récupéré pour fabriquer du papier hygiénique. Lors de la réalisation d'une ACV sur un système de production de papier hygiénique à base de fibre recyclée, il faut donc décider comment "allouer" diverses charges environnementales et besoins en ressources entre les deux systèmes intereliés : l'un produisant la fibre récupérée (le système de papier de bureau) et l'autre utilisant cette fibre récupérée comme une matière première (le système de papier hygiénique).

Dans le présent rapport, plusieurs méthodes d'allocation appliquées au recyclage en circuit ouvert sont expliquées, analysées et illustrées. Le lecteur doit savoir que l'Organisation internationale de normalisation (ISO) a publié des normes et directives portant sur un grand nombre des questions abordées dans le présent rapport. Les entreprises intéressées par les questions d'allocation qui se posent dans les études d'ACV et d'empreinte carbone devraient se familiariser avec les normes et directives ISO, dont une grande partie sont résumées dans le présent rapport. Une littérature et des pratiques abondantes à propos des normes et directives ISO ont vu le jour au fil du temps. Puisque ces informations supplémentaires sont accessibles aux entreprises, certaines d'entre elles sont examinés dans le présent rapport. Cependant, ces informations supplémentaires sont privées du consensus d'experts internationaux et de la réputation mondiale des normes et directives ISO; les entreprises doivent tenir compte de cette limitation.

Ce rapport met en évidence le potentiel qu'ont les résultats d'une ACV d'être grandement influencés par la méthode d'allocation choisie. Ce rapport peut être utilisé conjointement au bulletin technique n° 1002, qui lui porte sur les méthodes d'allocation des coproduits. De plus, ce rapport n'a pas pour objectif de restreindre l'utilisation des autres options méthodologiques offertes en vertu des normes et directives ISO, même si ces dernières ne sont pas couvertes dans ce rapport. Les entreprises sont responsables du choix et de la justification des méthodes d'allocation utilisées dans les études qu'elles effectuent et pour toute affirmations tirées de ces études.

Ronald A. Yeske

December 2012

METHODS FOR OPEN-LOOP RECYCLING ALLOCATION IN LIFE CYCLE ASSESSMENT AND CARBON FOOTPRINT STUDIES OF PAPER PRODUCTS

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ABSTRACT

In this document, the allocation methods for open-loop recycling most frequently used in pulp and paper case studies or presented as options in the ISO standards on life cycle assessment (LCA) are presented, illustrated, discussed and compared. It is shown that the choice of one allocation procedure over another can have a significant effect on the results of an LCA. In particular, the ISO standards on LCA require that sensitivity analyses be performed when several methods seem applicable. In part because of this, LCA may not be useful for obtaining unambiguous conclusions if the objective of the LCA is to compare virgin and recycled paper. When selecting an allocation method for recycling, the following should be kept in mind: the method should be consistent with the objective of the study; the set of values inherent to the selection of the method should be transparent; the selected method should preserve mass and energy balances (with the exception of the closed-loop procedure); and a similar allocation method should be applied to both the inflows and outflows of recovered material in the system boundary.

KEYWORDS

allocation, carbon footprint, life cycle assessment, paper products, recycling

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 1002 (December 2012). *Methods for co-product allocation in life cycle assessments and carbon footprints of forest products.*

Technical Bulletin No. 985 (May 2011). *Summary of the literature on the treatment of paper and paper packaging products recycling in life cycle assessment.*

Special Report No. 09-04 (April 2009). *Review of LCA allocation procedures for open-loop recycling used in the pulp and paper industry.*

MÉTHODES D'ALLOCATION APPLIQUÉES AU RECYCLAGE EN CIRCUIT OUVERT DANS LES ANALYSES DU CYCLE DE VIE ET LES ÉTUDES D'EMPREINTE CARBONE DES PRODUITS DE PAPIERS

BULLETIN TECHNIQUE N^{O} 1003
DÉCEMBRE 2012

RÉSUMÉ

Dans ce document, les méthodes d'allocation appliquées au recyclage en circuit ouvert les plus fréquemment utilisées pour les études de cas dans l'industrie des pâtes et papiers ou celles incluses comme options dans les normes ISO sur l'analyse du cycle de vie (ACV) sont présentées, illustrées, discutées et comparées. Il est montré que le choix d'une procédure d'allocation par rapport à une autre peut avoir un effet significatif sur les résultats d'une ACV. En particulier, les normes ISO sur l'ACV exigent que des analyses de sensibilité soient effectuées lorsque plusieurs méthodes semblent être applicables au cas à l'étude. En partie pour cette raison, l'ACV peut ne pas être utile pour obtenir des conclusions claires si l'objectif de l'ACV est de comparer le papier vierge au papier recyclé. Lors de la sélection d'une méthode d'allocation pour le recyclage, les éléments suivants doivent être pris en compte: la méthode doit être compatible avec l'objectif de l'étude, l'ensemble des valeurs inhérentes à la sélection de la méthode doit être transparent, la méthode choisie doit préserver les bilans de masse et d'énergie (à l'exception de la procédure en circuit fermé) et finalement, une méthode d'allocation similaire devrait être appliquée à la fois aux entrées et sorties de matières récupérées dans les limites du système considéré.

MOTS-CLÉS

allocation, affectation, empreinte carbone, analyse du cycle de vie, produits de papier, recyclage

AUTRES PUBLICATIONS DE NCASI

Bulletin technique n° 1002 (septembre 2012). *Methods for co-product allocation in life cycle assessments and carbon footprints of forest products.*

Bulletin technique n° 985 (mai 2011). *Summary of the literature on the treatment of paper and paper packaging products recycling in life cycle assessment.*

Rapport spécial n° 09-04 (avril 2009). *Review of LCA allocation procedures for open-loop recycling used in the pulp and paper industry.*

CONTENTS

TABLES

FIGURES

METHODS FOR OPEN-LOOP RECYCLING ALLOCATION IN LIFE CYCLE ASSESSMENT AND CARBON FOOTPRINT STUDIES OF FOREST PRODUCTS

1.0 INTRODUCTION

The North American pulp and paper industry is increasingly employing life cycle assessment (LCA) studies and closely related carbon footprint (CF) studies to assess the sustainability of its processes and products. LCA studies can serve multiple purposes such as educating customers and stakeholders about the environmental attributes of the industry's products and providing a basis for documenting improvements in these attributes over time.

One important characteristic of paper products is that they are usually recyclable. Indeed, the industry recycles a large proportion of its products. In both the US and Canada, 60 to 65% of paper consumed is recovered for recycling (ICFPA 2011). Two broad categories of recycling can be distinguished within LCA: closed-loop recycling and open-loop recycling. In closed-loop recycling, the recovered product from one system is reused within the same system. An example of this would be a system involving the domestic production of corrugated containers where all of the recovered old corrugated containers (OCC) are used in domestic containerboard production. Conceptually, the modeling of closed-loop recycling activities is relatively simple because all of the loads from the system can be assigned to the system's primary product, corrugated containers in this example.

However, in the pulp and paper sector, many product systems involve open-loop recycling, meaning that a significant portion of recovered paper products is reused as a raw material for producing other types of paper or paperboard, or even other types of products. An example of open-loop recycling would be a system producing domestic printing and writing paper, where 10% of the recovered paper is used in domestic printing and writing paper production while the remaining 90% is used as a raw material for the domestic production of other grades (e.g., boxboard, tissue).

Systems with open-loop recycling are a particular challenge in LCA because the same material provides a function for multiple products and hence, one must decide how to allocate the environmental load due to activities which are shared among these products. Closed-loop recycling does not require allocation because no processes are shared between more than one product system. The modeling of open-loop recycling, including allocation, has been described as the most complex methodological topic related to allocation in LCA (Werner 2005). In the case of paper, wood fiber is the material that can provide a function for different products and the shared activities can include virgin fiber production, recycling processes, and final disposal. The allocation in this case is even more complex because the fiber quality is altered in each recycling stage (cascade recycling). Some options for addressing fiber recycling in life cycle studies are addressed in ISO LCA standards (ISO 2006b) and in ISO 14049:2012 Technical Report (ISO 2012b), but questions have arisen as to how these standards are being applied in studies of paper and paperboard products (NCASI 2009, 2011). In this context, the objective of this report is to describe, discuss, and illustrate with forest products examples the most common approaches and methods for open-loop recycling allocation.

1.1 Disclaimer

The reader should be aware that the International Organization for Standardization (ISO) has issued standards and guidance addressing many of issues discussed in this report. Of particular relevance with respect to allocation questions are ISO standards ISO 14040:2006 and ISO 14044:2006, and ISO Technical Report ISO/TR 14049:2012. Companies interested in the allocation questions that arise in LCA and carbon footprint studies should familiarize themselves with this ISO material.

In this report, NCASI explains the material in the ISO documents and examines some of the interpretations of the ISO documents that have appeared in the literature and which are emerging in practice. NCASI has included this additional information because it addresses issues that forest products companies are likely to encounter in performing or interpreting LCA studies. It should be understood, however, that this supplemental material does not enjoy the international expert consensus and global recognition attached to ISO standards and guidance, a limitation that companies should take into account when relying on approaches not specifically addressed in ISO documents.

This report does not limit any of the options available to companies under ISO standards and guidance. Companies are responsible for selecting and justifying the methods used for allocation in studies they perform and for any claims based on those studies.

2.0 DEFINITIONS

Note: *Most of the definitions presented here are from the ISO 14044: 2006 standard cited as "(ISO 2006b)." Other sources were also used when necessary.*

Environmental Load
In this report, an environmental load is any input (resources, raw materials) or non-product output (releases, wastes) to or from a unit process or set of unit processes.

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, p. 5).

Product
A product is "*any good or service*" that is tangible or intangible (e.g., lumber or energy, respectively) (ISO 2006b, p. 2).

Product System
A 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, p. 4).

Closed-Loop Recycling
The ISO 14044 Standard does not formally define closed-loop recycling but it specifies that a closed-loop product system is a system in which *"material from a product is recycled in the same product system"* (ISO 2006b, Figure 2, p. 16).

Open-Loop Recycling
The ISO 14044 Standard does not formally define open-loop recycling but it gives the following technical description of an open-loop recycling product system: *"material from one product system is recycled in a different product system"* (ISO 2006b, Figure 2, p. 16). "Cascade recycling" is a form of open-loop recycling in which a material is used or recycled over and over again until its quality becomes too low to be used any further as a raw material in another product system (Ekvall 1994; Kim, Hwang, and Lee 1997; Tillman et al. 1994).

Flows
Flows are material or energy entering or leaving the product system being studied. **Elementary flows** have been "*drawn from the environment without previous human transformation"* or released into the environment without subsequent human transformation (ISO 2006b, p. 3). **Intermediate flows** are "*product, material or energy flow occurring between unit processes of the product system being studied*" (ISO 2006b, p. 4). **Product flows** are "*products entering from or leaving to another product system*" (ISO 2006b, p. 4).

Co-Product
A co-product is *"any of two or more products coming from the same unit process or product system"* (ISO 2006b, p. 3). While this definition would include within the co-products the studied product itself, the text of the ISO 14044 standard differentiates between three different concepts: the "product" that refers to the studied product, the "co-products" as defined above and "wastes", the "*substances or objects which the holder intends or is required to dispose of*" (ISO 2006b, p. 5). To avoid confusion, in this Technical Bulletin, the studied product is referred to as a co-product when it is produced from a unit process or a product system that produces more than one product, but is also always labeled "studied product".

> **Note:** It is important to understand the difference between a co-product and a waste because the environmental load of a shared process needs to be allocated between the co-products only and not the wastes. (Note, however, that waste management *processes* may require allocation if they are shared between two or more product systems.) The economic value of a material is often used to determine if it is a waste or a co-product. A material with a positive economic value is considered to be a co-product while a material with a negative economic value is considered to be a waste.

Determining and Dependent Co-Products
The ISO 14044 standard does not distinguish between different types of co-products. However, for the purpose of applying system expansion methods, the concepts of "determining" and "dependent" co-products can be helpful. A **determining co-product** is a co-product that determines the production volume of a shared process (Weidema 1999). A **dependent co-product** is a co-product for which the production volume is dependent on the production volume of the determining co-product. Any of the determining or dependent co-products can be studied in LCA. For instance, in a pulp mill, the determining co-product would the pulp and the dependent co-product could be turpentine. This is because the quantity of turpentine varies with the quantity of pulp that is produced. Any of these co-products could be the focus of an LCA study and thus would be the studied products.

Function
A function describes the performance characteristic of the product system or of a unit process. An **exported function** is generated within one product system but used in another one. Exported functions include the functions of co-products that are used in other systems, the processing of wastes from other systems and the raw material supply and waste management of recycling processes (Ekvall 1999b).

Allocation
Allocation is *"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, p. 4). The ISO 14044 standard (ISO 2006b) distinguishes three allocation approaches: 1) avoid allocation through system subdivision or expansion, 2) partition based on underlying physical relationships, and 3) partition based on another relation.

System Subdivision
System subdivision consists of *"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"* (ISO 2006b, p. 14).

System Expansion
System expansion consists of *"expanding the product system to include the additional functions related to the co-products"* (ISO 2006b, p. 14). Two system expansion models are encountered in the literature and not cited in the ISO LCA standards or technical reports: direct system enlargement and avoided burden (or substitution).

1) **Direct System Enlargement**
   Direct system enlargement is the modification of the objective of the study to fully account for the shared process by expansion of the system boundary to include all exported functions [modified from (Werner 2005)].

2) **Avoided Burden Method (Substitution)**
   The avoided burden method involves the expansion of the system boundaries and incorporation of substitution of those functions that are not of interest (exported functions) with an alternative way of providing it i.e., the process(es) or product(s) that the exported function supersedes, such that they are effectively removed from the studied system.

Material Balance Requirement
The ISO 14044 standard (ISO 2006b, p. 14) requires that *"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."*

Analyzed Decision
The analyzed decision is the decision that is to be informed by the LCA study. For instance, an analyzed decision can be to purchase one product versus another one, or to select amongst various policy options, etc.

Whole-System Model
"Whole-system model" is a term used in change-oriented LCAs to designate all unit processes affected by the analyzed decision or, in other words, the unit processes included in the system boundary by applying system expansion [adapted from Tillman et al. (1994) and (Werner 2005)].

Comparative Assertion
A comparative assertion is an *"environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function"* (ISO 2006b, p. 2).

Recycled vs. Recovered Material and Recycling vs. Recovery Processes
The ISO 14044 Standard defines a "raw material" as being *"primary or secondary material that is used to produce a product"* and specifies that *"secondary material includes recycled material"* (ISO 2006b, p. 3). It does not provide a definition of "recovered material." Also, while the ISO 14044 Standard (ISO 2006b, p. 15) speaks of recycling in general terms without mentioning the recycling process itself (e.g., "*recycling may change the inherent properties of materials in subsequent use*"), it does mention the recovery process as one for which *"specific care should be taken when defining system boundary"* (ISO 2006b, p. 15). The Standard does not provide any explanation on what is a recovery process. ISO 14049 (ISO 2012b) provides a little bit more insight. For instance, it presents an example in which *"paper recycling"* is described as having two functions: *"recovery of waste paper"* and *"production of de-inked pulp"* (ISO 2012b, Table 2, p. 5). Also, in the aluminum package example provided in ISO 14049 (ISO 2012b, paragraph 8.3.2), the recovered material includes the portion of used product that is not sent to disposal and any pre-consumer material that is sent to recycling. In this example, a recycling furnace transforms the recovered material into secondary aluminum. Some definitions of the recycling process can also be found in the literature. For instance, it has been described as the process(es) *"in which post-consumer material or production residues are collected and upgraded to secondary material"* (Lindeijer 1994, p. 29). Sometimes, the collection and sorting process are included in the recycling process. An example illustrating different system configurations for fiber recovery is shown in Figure 2.1.

The definition of the recycling process is also dependent on the allocation method used. For instance, if economic allocation is applied (see Section 6.3.3), then the end-of-life processes are considered "waste management" processes until the economic value of the recovered material goes from negative to positive. All the processing with positive economic value is then considered as the recycling process. The recovered/recycled material that leaves the system boundary of a product is referred to in this report as "**outflow of recovered/recycled material,**" while the recovered/recycling material that enters the system boundary of a product is referred to as "**inflow of recovered/recycled material**."

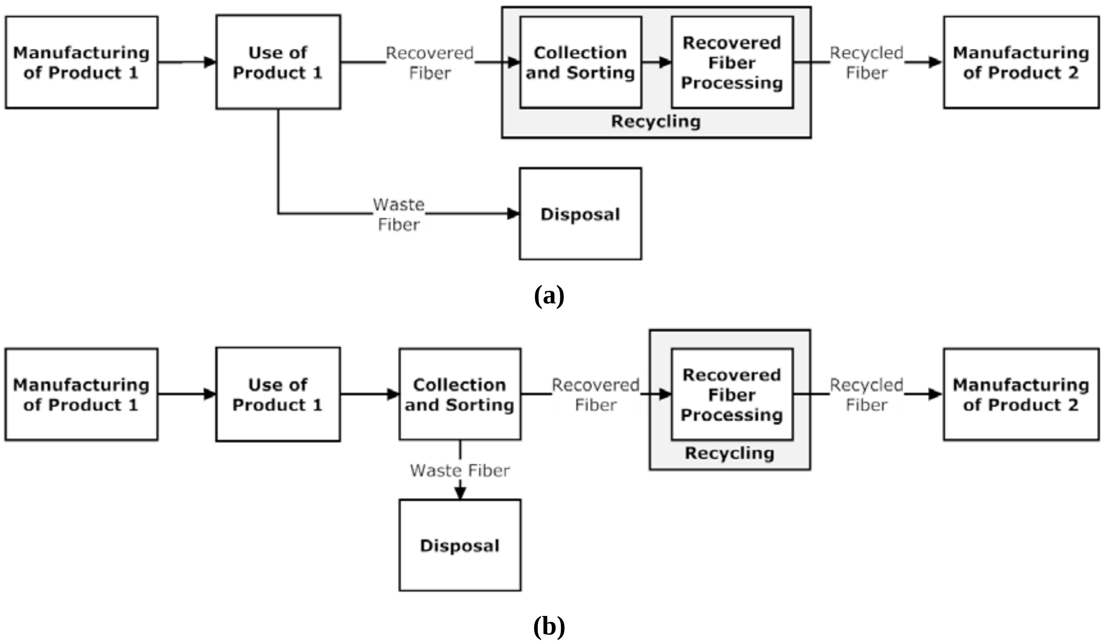

Figure 2.1 Recovered versus Recycled: A Fiber Example a) Collection and Sorting Are Included in the Recycling Process, and b) Collection and Sorting Are Not Included in the Recycling Process

Technosphere

The technosphere is the entirety of human activities covering production, consumption and disposal of products (Werner 2005).

3.0 LCA AND ALLOCATION

Life cycle assessment (LCA) is a methodology for the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (ISO 2006b, p. 2). The life cycle covers extraction of raw materials required for production, sometimes called the cradle, through final disposal of the product, sometimes called the grave.

LCA studies usually evaluate a variety of potential environmental impacts (e.g., global warming, acidification, smog, toxicity, etc.). Carbon footprint studies are similar to LCA studies, but they typically focus only on the global warming indicator. LCA and CF studies can serve multiple purposes, such as educating customers and stakeholders about the environmental attributes of the industry's products and providing a basis for documenting improvements in these attributes over time.

Life cycle principles and requirements have been specified in two standards from the International Organization for Standardization: the ISO 14040 and ISO 14044 standards. In addition, a series of technical reports and specifications were developed to support the application of LCA. These are summarized in Table 3.1.

Table 3.1 ISO LCA Standards, Technical Reports, and Technical Specifications

Document Number	Citation in This Document	Title
ISO 14040:2006	(ISO 2006a)	*Environmental Management -- Life Cycle Assessment -- Principles and Framework*
ISO 14044:2006	(ISO 2006b)	*Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines*
ISO/TR 14047:2012	(ISO 2012a)	*Environmental Management -- Life Cycle Impact Assessment – Illustrative Examples on How to Apply ISO 14044 to Impact Assessment Situations*
ISO/TS 14048:2002	(ISO 2002)	*Environmental Management -- Life Cycle Assessment -- Data Documentation Format*
ISO/TR 14049:2012	(ISO 2012b)	*Environmental Management -- Life Cycle Assessment -- Examples of Application of ISO 1404 4 to Goal and Scope Definition and Inventory Analysis*

The following subsections describe the LCA methodology, as specified in ISO standards (ISO 2006a, 2006b), in greater detail.

3.1 Concept of a Product System

LCA is used to model the life cycle of a product, referred to as a product system, which performs one or more defined functions. As illustrated in Figure 3.1, a product system is divided into a series of unit processes, which are linked together by intermediate flows and can also be linked in turn by flows to or from other systems. Product systems are linked to the environment by input elementary flows (natural resources) and output elementary flows (releases to air, water and land).

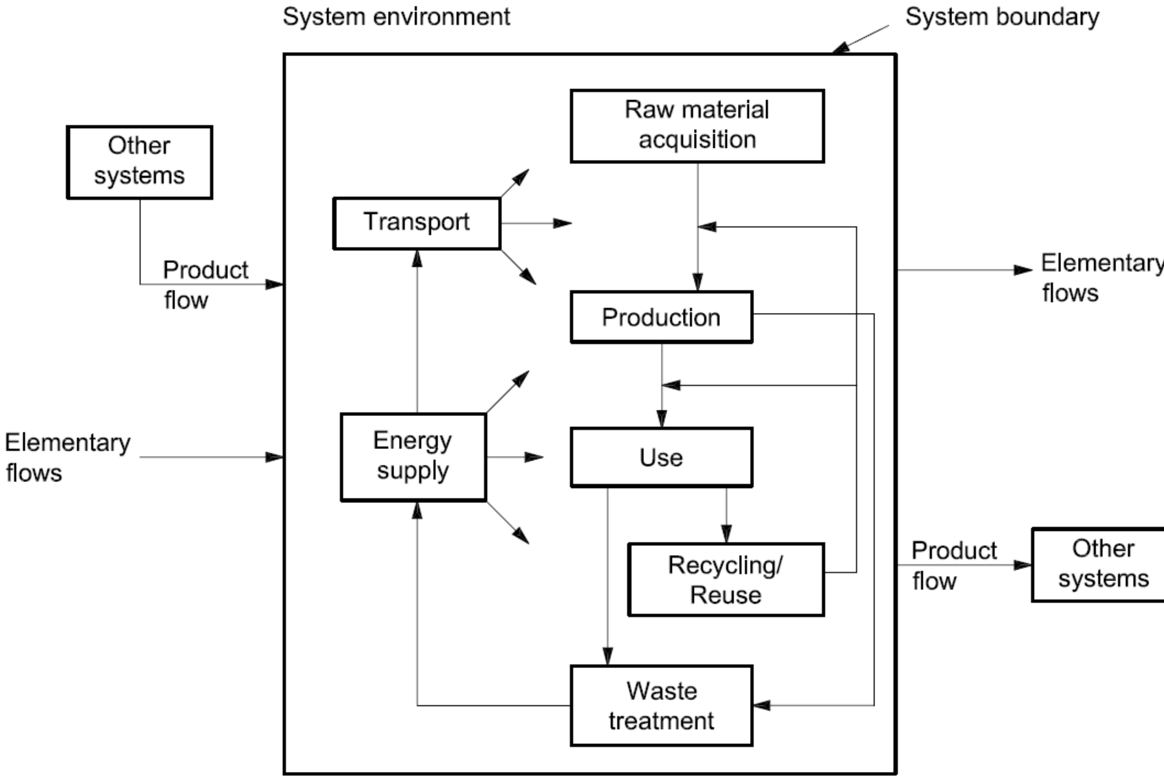

Figure 3.1 Example of Product System (ISO 2006a, p. 10)

3.2 Function and Functional Unit

An essential feature of LCA is that product systems are characterized by their function(s), or performance characteristic(s), and not solely in terms of their final products. A given product system can have a single function or multiple functions. LCA is generally focused on only one function, which is quantified using the functional unit. Examples of paper-related functions and functional units are presented in Table 3.2.

Table 3.2 Examples of Functions and Functional Units

Function	Functional Unit	Examples of Products
Packaging of beverage	To provide packaging for 12 cans of soft drink	Containerboard, plastic wrap
Printing surface	To provide 30 m^2 of printing surface for a given purpose	Uncoated freesheet, coated mechanical paper
Disseminating the news	Reading or watching the daily news	Newspaper, television, internet
Hand drying	To dry 100 pairs of hands	Paper towels, electric hand dryer

3.3 Four Phases of LCA

The ISO LCA methodology consists of four phases:

1) goal and scope definition;
2) inventory analysis;
3) impact assessment; and
4) interpretation.

The goal and scope definition is the phase of LCA where the objectives of the study, the product system (including boundary and function), and the procedures (including allocation procedures) to be used in the next phases are defined. Data are collected and relevant input and output flows are quantified during the inventory analysis phase. The impact assessment phase involves transforming flow information collected in the inventory phase into impact categories and then into impact indicator values. Impact indicator values, which are derived via characterization factors reflecting the relevant environmental mechanisms, are intended to assist in understanding and evaluating the magnitude of potential environmental impacts. Finally, the interpretation phase aims to provide additional analyses, conclusions, and recommendations based on the findings of the other phases.

3.4 What is Allocation?

When performing carbon footprint or LCA studies, the product system must be defined, as discussed previously. When several products (or functions) from different product systems share the same unit process or group of unit processes, allocation may be required. The shared processes are often referred to as multifunction (or multifunctional) processes. Allocation is needed in order to attribute the environmental load of the shared process(es) to the studied product (or function) and to each of the additional products (or functions) delivered by the shared process. The ISO 14044 standard (ISO 2006b) mentions two types of situations where allocation might be necessary: allocation related to co-products and allocation related to reuse and recycling.

The ISO 14044 standard does not further categorize the types of situations where co-product allocation might be necessary but two types of them are typically identified in the literature (Azapagic and Clift 1999; Baumann and Tillman 2004; Ekvall 1994; Tillman et al. 1994): multi-output processes (or coproduction) and multi-input processes (waste treatment processes).

A multi-output process, as illustrated in Figure 3.2, is a process which results in more than one output. A sawmill is an example of multi-output processes, where the products include lumber and chips. For instance, allocation would be required if an LCA was interested in lumber production and it was necessary to determine the fraction of the environmental load associated with the sawmill that should be allocated to lumber versus to chips.

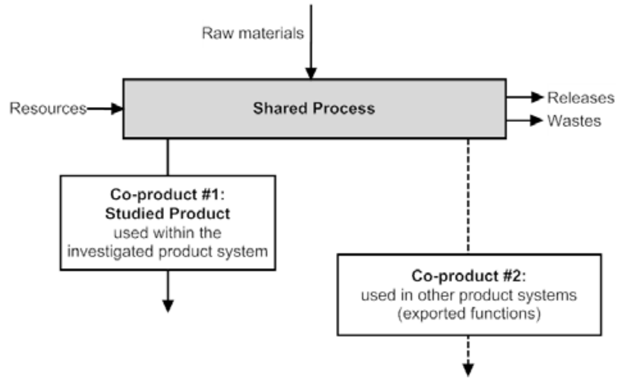

Figure 3.2 Allocation Related to Multi-Output Processes
[The functions or the functional flows are shown in dashed lines and the shared processes in gray.]

A multi-input process, as illustrated in Figure 3.2, is generally a waste management process that has input that consists of different products (more than one). An example of this is municipal landfilling in which several different products are disposed of at the same time. Allocation would be required if the LCA study was interested in only one of these products and hence it would be necessary to split the environmental load of the landfill process between the different products being disposed of.

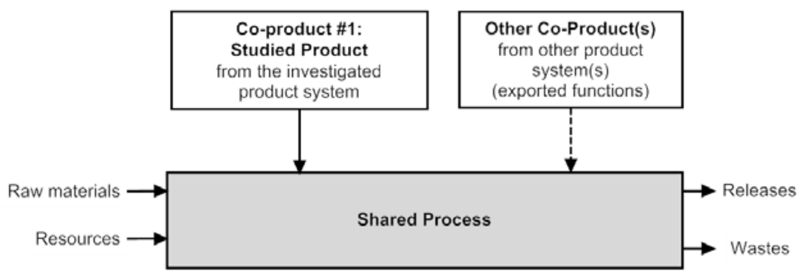

Figure3.3 Allocation Related to Multi-Input Processes
[The functions or the functional flows are shown in dashed lines and the shared processes in gray.]

In relation to recycling, the ISO 14044 standard discusses two technical descriptions for product systems, not to be confused with allocation procedures for recycling. These two are closed-loop product systems (generally described in the literature as closed-loop recycling) and open-loop product systems (generally described in the literature as open-loop recycling). Closed-loop recycling occurs when material from one product system is recycled within the same product system. Closed-loop recycling does not require allocation because no processes are shared between more than one product system. Open-loop recycling occurs when a material from one product system is recycled within another product system. A general illustration of this is depicted in Figure 3.4. In this example, the material is recycled two times, but it could be only one time, more than two and, in theory, an infinite number of times.

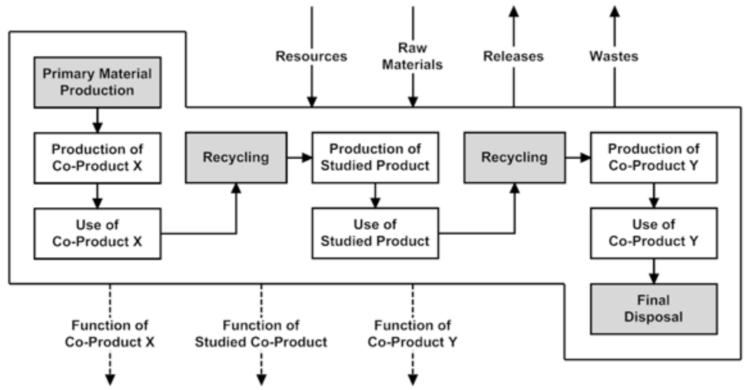

Figure 3.4 Allocation Related to Open-Loop Recycling
[The functions or the functional flows are shown in dashed lines and the processes most commonly recognized as shared in the literature are shown in gray.]

In parallel, the ISO 14044 (ISO 2006b, Figure 2, p. 16) standard distinguishes between recycling for which the *"material is recycled without changes to inherent properties"* and recycling in which *"recycled material undergoes changes in inherent properties"*. Closed-loop and open-loop product systems can include recycling of material with or without changes to inherent properties.

Where the material undergoes changes in inherent properties, two cases can occur: input-output processes and cascade recycling. Input-output processes (Werner 2005) provide one function through the treatment of an input and another function due to the production of an output product (usually a waste management process with a beneficial function, e.g., burning with energy recovery, landfilling with methane recovery and burning for energy, agricultural landspreading of wastewater treatment residuals, composting, etc.). These processes can occur in closed-loop or open-loop product systems. In the case of cascade recycling, material is used or recycled over and over again until its quality becomes too low to be used any further as a raw material in another life cycle system (Ekvall 1994; ISO 2012b; Kim, Hwang, and Lee 1997; Tillman et al. 1994). Cascade recycling generally occurs in open-loop product systems and not in closed-loop product systems.

ISO recommendations for situations involving recycling allocation as well as specific methods to address them are presented in Section 4. Open-loop recycling allocation is further discussed in NCASI Technical Bulletin 1002.

Open-loop recycling allocation is discussed in this report with an emphasis on cascade recycling allocation.

4.0 ISO 14044 RECOMMENDATIONS FOR ALLOCATION

In this section, the general recommendations of the ISO standard on LCA (ISO 2006b) regarding open-loop recycling allocation are summarized.

4.1 General Recommendations

The ISO 14044 Standard has the following general requirements for allocation (ISO 2006b, p. 14).

> *"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.[1]

Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach."

In addition,

"Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system."

4.2 The ISO 14044 Stepwise Procedure for Allocation

Different strategies can be used to resolve co-product allocation situations. The ISO 14044 Standard on LCA (ISO 2006b) provides the following stepwise procedure :

- **Step 1:** Avoid allocation through:
  a) System subdivision, or
  b) System expansion.
- **Step 2:** Partition using an underlying physical relationship, and
- **Step 3:** Partition using another relationship.

In this document, Steps 1 to 3 are referred to as "allocation approaches," while the different options within each of the approaches will be referred to as "methods."

Strictly speaking, the ISO 14044 Standard's stepwise procedure requires that, whenever possible, an approach to avoid allocation (i.e., subdivision or expansion) should be selected rather than an allocation approach. In practice, the selection of adequate allocation approaches and methods will have to consider the goal of the study, the available data and information, and the type of shared process to be allocated. More practically, the selection of an adequate approach and method depends on the goal of the study, the available data and information, and the type of shared process to be allocated (Ekvall and Weidema 2004; European Commission 2010; Tillman 2000; Werner 2005). The LCA ISO series (ISO 2006a, b) also recognizes that the decision context and the intended application should be considered when defining the product system studied but has been criticized for not accounting for various study objectives in its stepwise procedure for allocation (Ekvall and Finnveden 2001; Ekvall and Tillman 1997; Ekvall and Weidema 2004; Werner 2005).

The allocation approaches and methods, and their relationship with the study objective, are discussed in greater detail in the next sections.

Co-product allocation is further discussed in NCASI Technical Bulletin 1002.

4.2.1 *Open-Loop Allocation*

The ISO 14044 Standard (ISO 2006b) specifies that the stepwise procedure for co-product allocation also applies to recycling, especially for the recovery processes. However, additional elaboration compared to co-product allocation may be required because 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"* (ISO 2006b, p. 15). In other words, it is not necessarily only the recycling processes that are shared between different product systems. This aspect can apply to both input-output and cascade recycling problems, despite the fact that allocation related to

[1] This is referred to in this report as the mass balance requirement.

input-output processes is often dealt with using co-product allocation methods (see NCASI Technical Bulletin 1002).

Another reason for the recycling allocation to potentially require additional elaboration compared to co-product allocation is that recycling *"may change the inherent properties of materials in subsequent use"* (ISO 2006b, emphasis added), as in the case of cascade recycling systems for materials such as paper.

Several allocation approaches can be applied to open-loop recycling. As mentioned above, the first approach in the ISO 14044 hierarchy for co-products is to avoid allocation by dividing or expanding the system boundaries. Another way to avoid allocation, specifically for recycling allocation, is to approximate an open-loop system with a closed-loop system. In doing so, it is assumed that the use of recovered material displaces the use of virgin materials. The ISO standard allows for this only in cases "*where no changes occur in the inherent properties of the recycled material*[2]*"*(ISO 2006b, p. 15).

In cases where allocation cannot be avoided, the ISO standard (ISO 2006b) recommends application of an allocation procedure for the shared unit processes that uses, in order of preference, the following as the basis for allocation (partitioning methods), where feasible:

- physical properties (e.g., mass);
- economic value (e.g., market value of the scrap material or recycled material relative to market value of primary material); or
- number of subsequent uses[3] of the recycled material.

The approaches and methods specifically mentioned in the ISO 14044 LCA standard as well as its ISO 14049 accompanying report (ISO 2006b, 2012b) are discussed in this NCASI report. In addition, other methods that have been applied in the literature for pulp and paper case studies (NCASI 2009, 2011) are also discussed. All the methods that will be discussed in this document are summarized in Table 4.1.

[2] The ISO standard uses the term "recycled material" to designate a type of secondary raw material. This terminology can be confusing. Hence, in this document, "recovered material" will be used instead.
[3] In this report, the method that uses the number of subsequent uses as the basis for allocation will be referred to as the "Number of Uses" (NOU) method.

Table 4.1 Recycling Allocation Methods Discussed in this Document

ISO Stepwise Procedure	Method Name	Section of This Report
Avoid allocation through system subdivision	N/A	6.2.1
Avoid allocation by applying a closed-loop procedure	Closed-loop procedure	6.2.2
Avoid allocation through system expansion	Direct system enlargement	6.2.3.1
	Substitution: credit for end-of-life recycling	6.2.3.2
	Substitution: credit for use of recovered material	6.2.3.3
	Substitution: Ekvall	6.2.3.5
Partitioning using underlying physical relationship	N/A	6.3.1
Partitioning using other relationships	Physical properties, mass	6.3.2
	Economic value	6.3.3
	Number of uses (NOU)	6.3.4
Other methods not mentioned in ISO 14044 or ISO 14049	Cut-off	6.3.5.1
	Extraction-load	6.3.5.2
	50/50	6.3.5.3
	Others: quality losses, disposal load	6.3.5.4

4.2.2 Relationship between the Study Objective and the Choice of an Allocation Approach

While the ISO 14044 standard does not provide any requirement that relates the choice of an allocation approach to the study objective, other authors have been distinguishing between two approaches based on the study objective: 1) one which assigns environmental loads to a specific product system typically as an account of the history of the product, and 2) one which evaluates the environmental consequences of a change in the product system. These two approaches, which are briefly mentioned in an informative Annex of the ISO 14040 Standard (ISO 2006a), have been referred to, respectively, by authors as

- accounting or attributional LCA (Baumann and Tillman 2004; Ekvall and Weidema 2004) [although other terms have also been used in the literature, for instance information-oriented LCA (Baumann 1996), (Weidema 1998), descriptive LCA (Ekvall 1999a; European Commission 2010), attributional LCA, retrospective LCA (Ekvall, Tillman, and Molander 2005; Tillman 2000), and bookkeeping LCA (European Commission 2010); and
- change-oriented or consequential LCA (Baumann and Tillman 2004; Weidema 1998; Ekvall and Weidema 2004; European Commission 2010) [although other terms such as decision support LCA have also been used in the literature (European Commission 2010; Ekvall, Tillman, and Molander 2005; Tillman 2000; Werner 2005)].

The diversity of terms for those two approaches illustrates the lack of international consensus and the need for complete transparency in describing the approach used.

Although the ISO 14044 standard (ISO 2006b, p. v) recognizes that *"the scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study",* it does not provide any guidance on how the allocation procedures should be selected in this context (Curran 2007; Ekvall and Finnveden 2001; Werner 2005) and does not propose different rules for the two approaches mentioned above.

A number of options have been proposed in the literature to address this flexibility in ISO 14044 (Baumann 1996; Baumann and Tillman 2004; Ekvall 1999a; Ekvall, Tillman, and Molander 2005; Ekvall and Weidema 2004; European Commission 2010; Tillman 2000; Weidema 1998; Werner 2005).

Because accounting LCA does not imply any decision support but is rather of a descriptive character, it has been proposed in the non-ISO literature that the LCA model can be established in a way that describes the system as it is. In this context, an allocation approach based on partitioning would be preferred to an approach involving system expansion. In some cases, one might be interested in including the potential interactions of one product system with another one, although the objective of the study is to describe the environmental load attributable to a given product. For instance, if a paper mill sells electricity to the grid, it might be interested in including in the LCA of paper the benefits from selling this electricity. In this case, some sort of system expansion would be required. This situation will be referred to, in this document, as accounting LCA including the existing benefits outside the studied system.

Change-oriented LCA implies that the study is interested in the consequences of a given decision on the product system. It involves a change in the production level of a given material. In this case, it has been proposed in the non-ISO literature that the LCA model can be established in a way that reflects as much as possible the consequences of a change and system expansion approaches are usually preferred over partitioning approaches.

Many pulp and paper LCA case studies are available in the literature, most of them addressing questions best examined with accounting LCA.

- What are the main contributors to the life cycle environmental performance of a paper product?
- What are the environmental impacts attributable to a given paper product? How does the environmental performance of a paper product vary from year to year?
- How does the environmental profile of a virgin paper product compare with the environmental profile of a recycled paper product?
- How does the environmental profile of a paper product that is used for a given function compare with the environmental profile of an alternative non-paper product that is used to fulfill the same function?

In using accounting LCA to examine these questions, an allocation procedure must be selected to address recycling. The choice of the allocation procedure will have an effect on the results of the LCA and thus, on the answer to the question. Case studies will be presented later to illustrate this.

The main change-oriented question that has been posed in pulp and paper case studies is related to the various waste management options for paper. However, it is not always asked in a way that it is clearly a change-oriented question. The question that is most often asked is:

- What is the preferable waste management option for paper from an environmental perspective: landfilling, incineration with energy recovery, or recycling?

This question could be interpreted as an accounting-type question if it is strictly focused on a comparison of options as they currently exist. More commonly, however, it is asked in a context that implies a change-oriented question, such as:

- What is the environmental consequence of increasing paper recycling?

Change-oriented questions require that system expansion be used and thus, are not subject to the uncertainty related to the choice of an allocation procedure. However, they are subject to the limitations and challenges associated with system expansion methods. These are also discussed below.

5.0 DEFINITION OF SHARED PROCESSES AND SYSTEM LEVELS

The allocation approaches that are available in the literature for cascade recycling can be discussed based on the unit processes that are considered to be shared and based on the system level that is used to address the allocation. These two aspects are discussed in this chapter.

5.1 Defining Shared Processes

One of the main challenges in open-loop recycling allocation, especially in cascade recycling allocation, is that there is no agreement on what the shared processes are (i.e., processes that need to be allocated between the various usages of the material). This section provides an overview of different authors' perspectives on this in relation to what is available in the ISO 14044 Standard and ISO 14049 Technical Report.

The ISO 14044 Standard (ISO 2006b, p. 15) specifies that *"recycling […] may imply that the inputs and outputs associated with unit processes for* ***extraction and processing of raw materials***[4] *and* ***final disposal of products*** *are to be shared by more than one product system"* and that *"specific care should be taken when defining system boundary with regard* ***to recovery processes****"* [emphasis added]. In the same vein, some authors (Ekvall 1994; Ekvall and Tillman 1997; Kim, Hwang, and Lee 1997) argue that virgin material production processes, waste management processes and recycling processes are shared between the different products in the material cascade.

On the other hand, Werner (2005) argues that, to determine under which circumstances unit processes are shared, it is necessary to evaluate the range of responsibilities of the manufacturer of the material and energy flows related to the product. To do that, according to Werner (2005), two approaches based on economic science are available in the literature. The first one accounts for the environmental impacts within the product system in which they directly occur. The second one, the asset approach, extends the range of responsibilities of the manufacturer by considering the material as an asset with an embedded environmental load from its virgin material production and final waste management unit processes.

In the first approach, each product is attributed the environmental load directly caused by that product. The virgin material production is allocated to the first product in the material life cycle. Waste management is allocated in the product system where it occurs. The recycling process is generally allocated to the user of recovered material. This approach does not account for environmental load that occurred in the past nor does it postpone the accounting of environmental load in the future. Werner argues that, by ignoring environmental load that occurred in the past, this approach may result in suboptimal results for accounting LCAs (see an example of this for the cut-off method in Section 6.3.5.1). However, accounting for environmental load that occurred in the past for change-oriented LCAs will lead to systematic errors. On the other hand, according to Frischknecht (2010), it is a risk-averse approach because it does not allow for postponing the accounting of environmental load in the future. This approach is usually used in public life cycle inventory databases. The main allocation method within this approach is the cut-off method described in Section 6.3.5.1.

Using the second approach, the asset approach, the environmental load of virgin material production and final waste management is allocated to all products in the material life cycle based, for instance, on the number of uses (see Section 6.3.4) or losses of material quality (see Section 6.3.5.4). An allocation procedure needs to be selected for the recycling process. Using this approach, the LCA of a given product system may account for environmental load that occurred in the past and, at the same time, a portion of the accounting of environmental load that directly occurs in the studied product system may be postponed into the future. According to Werner (2005), when applied in accounting LCA, this approach emphasizes the importance for material efficiency in the context of sustainable development. On the other hand,

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[4] Virgin or recovered.

applying this approach would result in including, in the boundary of a given product system, activities and their related environmental load that are outside the control of the entity performing the study. It is viewed as a risk-tolerant approach because it allows for postponing of the accounting of environmental load, under the assumption that recycling will occur.

Werner (2005) argues that the choice between the two approaches in accounting LCA should be based on the product type and its market characteristics. Werner also stresses that environmental load that occurred in the past should not be accounted for in change-oriented LCAs.

Other authors have visions of the shared process that can be described, in full or in part, according to these two approaches. Ekvall (1994) and Axel Springer Verlag AG, Stora, and Canfor (1998) suggested that the environmental load of the full material life cycle can be split across all products in the material life cycle. In the ISO example related to application of the number of uses method, presented in ISO 14049 technical report (ISO 2012b), an accompanying document to the ISO 14044 Standard, processes associated with the production of the virgin paper product, including papermaking, are assumed to be shared (see Section 6.3.4). Final disposal and the recycling process are not considered to be shared (at least there is no discussion on that topic). Ekvall and Tillman (1997) and Strömberg et al. (1997) mentioned that, in a cascade of material, the allocation efforts can be reduced by allocating the environmental load associated directly with one product to that same product. This includes the manufacturing of the product (e.g., papermaking and conversion) and the use of that product. Hence, the shared processes are considered to be the production of the virgin raw material, recycling processes, and final waste management. Guinée, Heijungs, and Huppes (2004) assumed that all processes in the virgin product system are shared between the virgin product and the subsequent uses of the recovered material except for the disposal of the non-recovered fraction. The recycling processes are not shared.

5.2 System Levels

In the literature, a dichotomy exists between allocation approaches that focus on the two product systems connected by the recycling process and approaches that consider the full material life cycle (Heijungs 1994). That is, open-loop recycling allocation has been discussed based on the different system levels (Ekvall and Tillman 1997).

- Two product systems connected by the recycling process:
  - Process level (designated by boundary A in Figure 5.1, focusing on the recycling processes and the functions they provide);
  - Product system level (designated by boundary B in Figure 5.1, focusing on the life cycle of the products and the functions provided by the product system);
- Consideration of the full material life cycle:
  - Material life cycle level (designated by boundary C in Figure 5.1, focusing on the life cycle of the fibers).

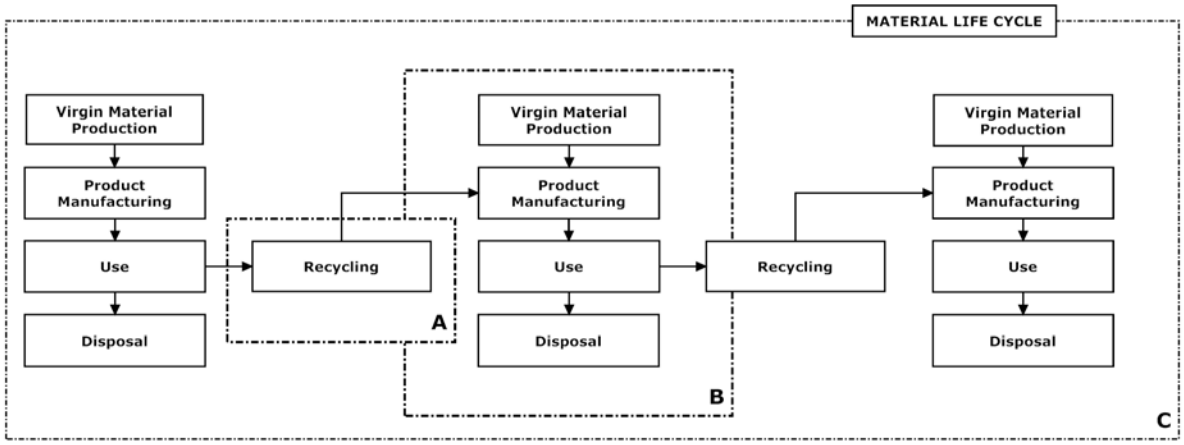

Figure 5.1 System Levels for Cascade Recycling
[Adapted from Werner (2005)]

5.2.1 *Process Level*

At the process level, only the recycling process needs allocation (i.e., is considered to be shared). The situation involving allocation is resolved by considering recycling as bi-functional with the following functions:

- providing waste management for the upstream product system; and
- providing secondary raw material for the downstream product system.

At this system level, the virgin material production and waste management processes are not considered to be shared between different products. Accordingly, the environmental load associated with the virgin material production process is allocated to the first product using that material and the environmental load for waste management processes is allocated to the product system where the material is disposed of.

Process level analyses are usually easy to apply but have some disadvantages, in that virgin material production and waste management are not considered to be shared as discussed in the ISO standard (ISO 2006b) and the effects of recycling on virgin material production and waste management are not reflected.

5.2.2 *Product System Level*

At this system level, the entire product system is considered to be shared by providing two or more functions:

- the function of the studied product; and
- a waste management function for the upstream product system and/or a raw material production function for the downstream product system.

This approach allows the inclusion of environmental loads of processes that are not directly linked to the studied product system. However, only interactions between the studied product system and those immediately upstream or immediately downstream are considered. This system level also requires a separation to be made between the various product systems, i.e., deciding where one stops and the next one starts.

Werner (2005) argues that using a product system level allows application of an asset approach (described in Section 5.1) without having to model the whole, possibly hypothetical, material life cycle but rather by only considering interactions with other product systems directly connected to the product system being studied.

5.2.3 *Material Life Cycle Level*

In accounting LCAs, when addressing the allocation situation at the material life cycle system level, the entire material life cycle is considered to be a multifunction process providing the functions for all products in the life cycle. In other words, all the processes in the material life cycle need to be evaluated in terms of allocation. That said, some processes can clearly be associated with only one specific product and thus should not be allocated (Ekvall and Tillman 1997). These include, for instance, the production and use of the specific products under study. Allocation methods are required for the other processes that cannot be clearly associated with a specific product (shared processes, see Section 5.1). In change-oriented LCAs, this system level involves the inclusion of all affected processes within the system boundary, including the processes that are affected through a propagation of effects in the material life cycle (whole-system model).

5.2.4 *Allocation Methods in the Context of System Levels*

When dealing with allocation at the process level, the allocation of the environmental load of the recycling process between the two functions can be made using partitioning methods developed for co-products (see NCASI Technical Bulletin 1002). However, physical properties (e.g., mass) are inadequate parameters for the description of the functionality of waste management and secondary material production. This is because of the difficulty of identifying a physical property that reasonably relates both to the waste management and raw material production functions. For this reason, it has been argued that only economic allocation (described in Section 6.3.3) is applicable for process level analysis (Huppes 1992; Werner 2005). That said, the cut-off method (described in Section 6.3.5.1) allocates 100% of the recycling process to the product using the recovered material, and thus does not have the problem of determining an adequate parameter for the description of the functionality of waste management and secondary material. Therefore, it can also be applied at the process level.

Werner (2005) states that allocation methods based on substitution (closed-loop procedure and substitution methods) fall within the product system level or material life cycle level. On the other hand, Ekvall and Tillman (1997) argue that allocation at the product system level is not well established in practice and that the substitution methods rather apply at the process level or at the material life cycle level. Werner's view on this is that methods at the process level cannot include processes that occur in other product systems.

For accounting LCAs, situations involving allocation can be dealt with at the material life cycle system level either by expanding the system boundaries to the full material life cycle (direct system enlargement, see Section6.2.3) or by allocating the environmental load of the entire material life cycle to all functions provided by the material, using appropriate partitioning methods (Werner 2005). Partitioning methods to do this include, for instance, mass allocation (see Section 6.3.2), economic allocation for pseudo-recycling (see Section 6.3.3) and the number of uses method (see Section 6.3.4). For change-oriented LCAs, it is necessary to expand the system boundary to apply a whole-system model[5]. This can be done, for instance, by using price elasticities for the determination of the effects of marginal changes in a "pre-defined" whole-system [quoted after Werner (2005), proposed by Ekvall (2000), see Section 6.2.3.5], or based on mathematical models (linear programming) that depict the changes in an entire technological system caused by marginal changes [quoted after Werner (2005), proposed by Azapagic and Clift (1999), see Section 6.3.5.4]. Werner (2005) argues that although the above mentioned methods are based on a whole-system model, to date there has been no effort towards including product systems within a whole-system model that are not directly connected with the product system studied.

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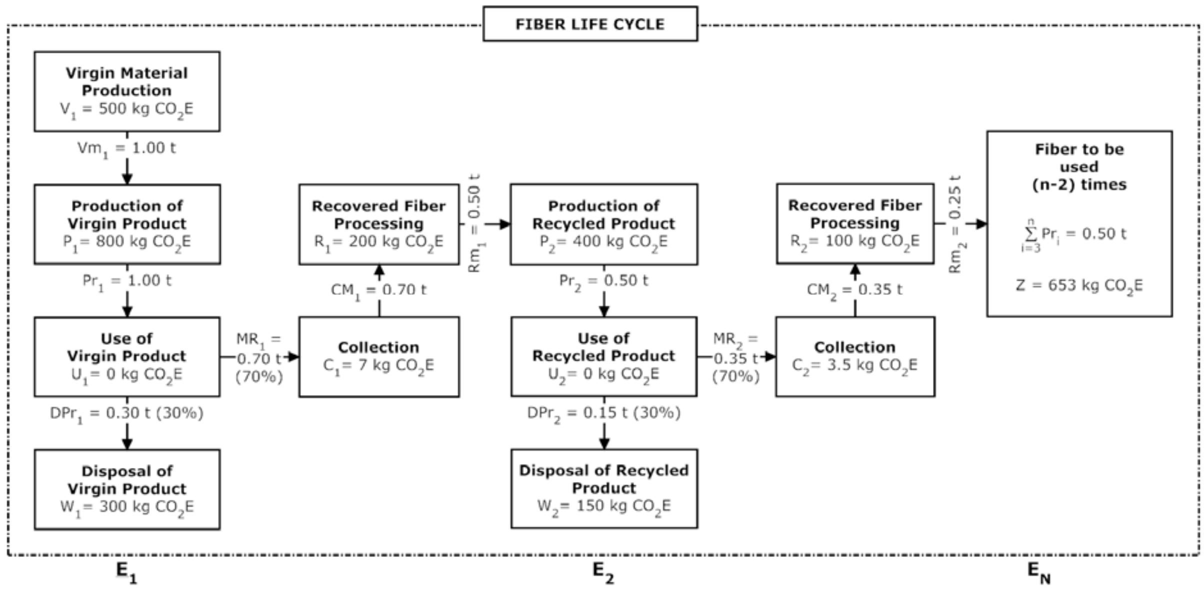
[5] Term used in change-oriented LCAs to designate all unit processes affected by the analyzed decision or, in other words, the unit processes included in the system boundary by applying system expansion.

6.0 METHODS FOR CASCADE RECYCLING ALLOCATION

As briefly mentioned in the preceding sections, many different methods have been proposed in the literature for open-loop recycling allocation and more specifically for cascade recycling systems. This document focuses on the methods presented in the ISO LCA standards and accompanying report (see above), as well as on methods other than these that have been used in pulp and paper case studies [see NCASI Special Report 09-04 (NCASI 2009) and Technical Bulletin No. 985 (NCASI 2011)]. A list of these methods is provided in Table 4.1. In the next sections of this document, these methods are explained, illustrated using a common example presented below, and discussed, with an emphasis on their relationship to the ISO 14044 Standard.

6.1 Example for Illustrating the Allocation Methods

An open-loop recycling allocation situation occurs when used material from the studied system is recycled into another product system or when the studied system uses material that is recovered from another product system. In other words, this situation can be caused by outflows of recovered material from the product system or inflows of recovered materials to the studied product system. In this report, a hypothetical example, presented in Figure 6.1, is used to illustrate various allocation methods for open-loop recycling.



In this example, virgin material is produced (Vm_1 e.g., kraft pulp) to produce virgin paper product (Pr_1 e.g., virgin uncoated freesheet). This product is used and 70% is recovered for recycling (MR_1). The other 30% is disposed of (DPr_1). The collected material (CM_1) is processed to produce recycled material (Rm_1 e.g., de-inked pulp with a loss of 0.28571 t/t) that is used for production of recycled paper product (Pr_2) which, in turn, is used and recovered at a rate of 70% (MR_2). It is assumed that an additional 0.50 t of paper will be produced in the "n-2" subsequent uses of that recovered fiber. Hypothetical carbon footprint values are given for each of the unit processes presented. "N" is the total number of times a fiber is used. In this figure, the fiber is used n times:

- Used in the virgin product (n=1);
- Used the first time in a recycled product (n=2); and
- Used "n-2" times in subsequent products.

Nomenclature:
Vm_i: Quantity of virgin material i, V_i: Environmental load of virgin material production[6], Pr_i: Quantity of product i, P_i: Environmental load of the production of product i, U_i = Environmental load of use of product i, DPr_i: Quantity of product i to disposal (= 30% x Pr_i), W_i: Environmental load of product disposal, MR_i: Quantity of used product i for recovery, CM_i: Quantity of used product i after collection, C_i: Environmental load of collection of used product, Rm_i: Quantity of recycled material from product i; R_i: Environmental load of recovered fiber processing.

The environmental load of the various unit processes are: V = 500 kg CO_2E/t Vm_i, C = 10 kg CO_2E/t CM_i, R = 400 kg CO_2E/t Rm_i, P = 800 kg CO_2E/t Pr_i, W = 1000 kg CO_2E/t DPr_i. Z is the environmental load occurring downstream in the material life cycle i.e., due to the subsequent uses and disposal of the fiber not shown on the figure (i.e., $Z = \sum_{i=3}^{n} V_i + P_i + U_i + W_i + C_i + R_i$). All the examples presented in this report are applied to Pr_1 (the virgin product) and Pr_2 (one recycled product). However, Z is necessary to demonstrate some of the methods.

Figure 6.1 Example for Illustrating the Allocation Methods

In the example above, the focus is on "cascade recycling" i.e., on cases where a material, such as paper, is used or recycled over and over again until its quality is inadequate to enable its further use as a raw material in another life cycle system (e.g., it becomes a waste). Different allocation methods from those

[6] In this report, global warming (in CO_2E) is used an example of environmental indicator referred to as environmental load.

discussed below would be required if the last usage of the fiber was for energy production. The example below considers "n" usages of the fiber in paper products. All allocation equations provided in this document are valid for cases where the first usage of the fiber is fully from virgin material and the subsequent usages of the fiber are fully from recycled material. Some equations are not valid for cases where there is input of virgin material in the subsequent uses of the material. This limitation is clearly indicated for relevant equations provided below.

6.2 Methods Used to Avoid Allocation

The ISO 14044 Standard (ISO 2006b, p. 14) specifies that requirements for co-products also apply to recycling. This means that allocation should be avoided, where possible by "*1) 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*" (referred in this report as "system subdivision"), or *"2) expanding the product system to include the additional functions related to the co-products"* (referred in the report as system expansion). The standard also provides a third way of avoiding allocation: applying a closed-loop procedure. These three approaches are discussed in this section.

6.2.1 *System Subdivision*

Subdivision consists of the division of the multifunction process into sub-processes, and collection of separate data for each sub-process. System subdivision is of limited usefulness to open-loop recycling allocation (Ekvall and Finnveden 2001). For this reason, it is not discussed further.

6.2.2 Closed-Loop Procedure

Modeling an open-loop recycling system as a closed-loop system can be used to avoid allocation (ISO 2006b, 2012b; Luebkert et al. 1991; Werner 2005). The ISO 14044 Standard distinguishes between two technological descriptions of product systems: closed-loop product systems, and open-loop procedures. It also distinguishes between closed-loop and open-loop allocation procedures for recycling. The ISO 14044 Standard specifies that *"a closed-loop allocation procedure applies to closed-loop product systems [and] to open-loop product systems where no changes occur in the inherent properties of the recycled material"* (ISO 2006b, p. 15). This is illustrated in Figure 6.2.

		INHERENT PROPERTIES OF THE MATERIAL	
		No changes	**Changes**
TECHNICAL DESCRIPTION OF THE PRODUCT SYSTEM	**Closed-loop product system**	Closed-loop product system with no changes in inherent properties	Closed-loop product system with changes in inherent properties (including input-output processes)
	Open-loop product	Open-loop recycling with no changes in the inherent properties	Open-loop recycling with changes in the inherent properties (including input-output processes and cascade recycling)

Figure 6.2 Recycling Cases and Application of Allocation Procedures for Recycling
[Light gray cells: closed-loop procedure applies. Dark gray cells: open-loop procedure applies.]

Neither the ISO 14044 (ISO 2006b) Standard nor its ISO 14049 accompanying technical report (ISO 2012b) provide more explanation as to what "changes in inherent properties of the recycled material" actually means. Also for applying a closed-loop procedure to an open-loop product system, the product system being analyzed needs to be modeled as participating in *"product independent material pools"* (ISO 2012b, p. 30) by delivering recovered material into an external material pool and being supplied with recovered material from that same external material pool. The ISO 14049 Technical Report further specifies that *"if the import and export of secondary raw material between the pool and product specific life cycle are equivalent, the product specific system can be modelled as closed loop recycling without any problem*" (ISO 2012b, p. 30). The technical report does not specify whether the import and export needs to be equivalent in terms of quantity and/or type/quality of recovered material. The following interpretations of "equivalent" and "no change in the inherent properties of the recycled material," and thus, of when the closed-loop procedure can be applied, can be found in the literature.

- One interpretation is that a closed-loop procedure can be applied to open-loop systems if the recovered material is used to produce a product of very similar quality or if it would be possible to recycle the recovered into the same product (Luebkert et al. 1991).
- According to Werner (2005), determining whether a closed-loop procedure can be applied to an open-loop system requires predefining the conditions under which this assumption can be made, including deciding which parameters (physical, chemical, biological, technical or economic) should be used to define the equivalency of the import and export, and the extent to which deviation of these parameters is tolerable. Werner specifically mentions fiber length as an example of a parameter that can be used to determine whether the inherent properties are changed. Change in inherent properties is one of the main reasons why a material has a limited service life (Werner 2005). In this context, it is important to mention that wood fiber gets shorter each time it is processed in the recycling process. When fibers become too short or brittle to bond with each another, the physical and performance characteristics of the paper sheet may be compromised. Fibers can be reused between four to nine times depending on the new paper grade that is being produced (GreenBlue 2011). Consequently, with Werner's interpretation of "change in inherent properties," a closed-loop procedure would not be adequate for a paper product, at least for recycling processes that significantly alter the fiber length (i.e., at a level that would be greater than the tolerable deviation). The definition of a tolerable deviation is not mentioned.
- The closed-loop procedure is applicable for materials that do not degrade significantly in quality when being recycled and when it can be assumed that recycled material replaces virgin material. For degradable material such as paper, the closed-loop procedure is less suitable (Baumann and Tillman 2004).

When a closed-loop procedure is applied to an open-loop system, it is assumed that recovered material leaving the system boundary of the investigated product will replace virgin material in subsequent product systems (Werner 2005). Using this approach, the material losses are not attributed to the product system that causes them but rather to the product system that has an outflow of recovered material. Also, this assumes that the recycled material is fully substitutable for virgin material.

The ISO 14049 Technical Report (ISO 2012b) describes three cases of open-loop systems that can be dealt with using a closed-loop procedure. The underlying assumption, as illustrated in Figure 6.3, is that the product system participates in a recovered material pool by delivering secondary raw material into the pool and by being supplied with secondary material from the same pool, meaning that, in theory, for a closed-loop procedure to apply to open-loop recycling, the quantity and type of recovered material supplied to the pool should be similar to the material taken from the pool (X should be similar to Y in Figure 6.3).

The recycling of the same material can occur many times and, in some cases, the material can theoretically be permanently kept from disposal through continual recycling. This is not the case with paper products because each recycling loop further degrades the fiber until it can no longer be used.

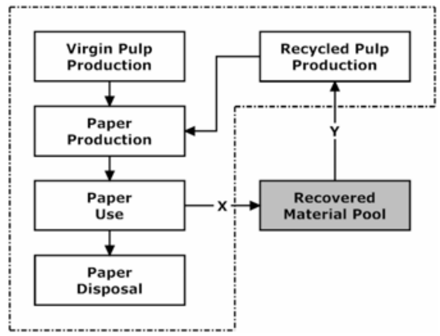


Figure 6.3 Schematic Illustration of Open-Loop System for Which a Closed-Loop Procedure Can Apply

The three cases presented in ISO 14049 (ISO 2012b) are:

- Case 1 – The studied product system delivers and uses equivalent quantities of recovered material from the pool (X = Y);
- Case 2, defined by ISO 14049 (ISO 2012b) as cases where *"an adjusted technology split"* is used – There is a net inflow (2a) or a net outflow (2b) of recovered material, and the virgin and recovered material processing applied in the studied product system is identical or very similar to that applied in the rest of the recovered material market, and the inherent properties of the virgin and recycled products are identical or similar; and
- Case 3 – The processes related to virgin and recovered material processing are different in the studied product system than in the rest of the recovered material market, and/or the inherent properties of the virgin and recycled products are different.

These are discussed further and illustrated in the next sections.

6.2.2.1 *Case 1 – Equivalent Inflows and Outflows*

Where the inflows and outflows of recovered material between the studied product system and the recovered material pool are equivalent, the system can be modeled directly as a closed-loop system by including the related portion of the material pool within the boundary, as illustrated in Figure 6.4. In this case, there is no need for allocation and hence the environmental load of the product system can be calculated directly. In practice, this case almost never occurs; hence, it is not discussed further.

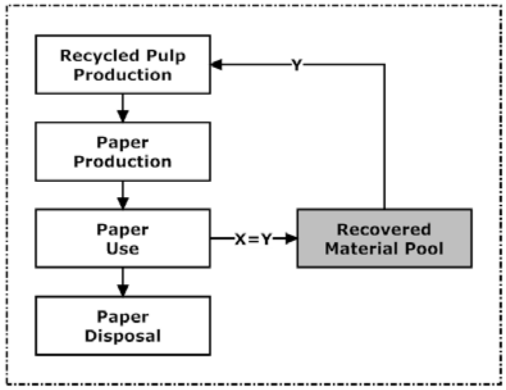


Figure 6.4 Closed-Loop Procedure Applied to Open-Loop Recycling, Equivalent Inflow and Outflow

6.2.2.2 *Case 2a – Net Inflow: Similar Processes*

The second case is when there is a net inflow or outflow of recovered material from the material pool, the virgin and recovered material processing are either identical or not very different in the studied product system and in the rest of the recovered material market, and the inherent properties of the virgin and recycled products are identical or similar. The case described here focuses on net inflows of recovered material. An example of this is a system producing corrugated containers from a combination of virgin kraft fiber and recovered fiber derived primarily from old corrugated containers. In this case, the closed-loop procedure can be applied by adjusting the technology split of virgin material production and recovered fiber processing to match the recovery rate.

The general equation for calculating the environmental load using the closed-loop procedure, $E_{i,CL}$, is

$$E_{i,CL} = V'_i + P_i + U_i + W_i + C_i + R_i$$

where P_i is the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and V'_i is calculated as follows:

$$V'_i = V \times (Rm_{i-1} + Vm_i - \beta_i Rm_i)$$

β_i is an equivalency factor between virgin and recycled material (e.g., in this case the quantity of virgin pulp equivalent to a given quantity of recovered pulp) and V is the environmental load of virgin pulp production per ton of virgin pulp (see Figure 5.1).

In Figure 6.5, which is based on Figure 4.1, a simplified recycling model is used to illustrate the case where there is a net inflow of material from the pool.

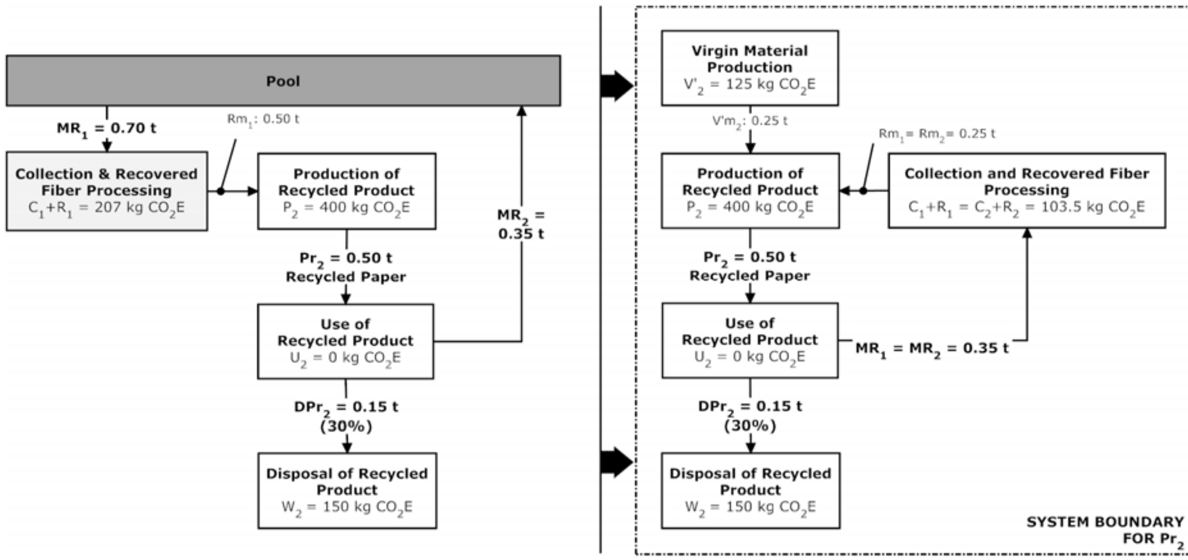


Figure 6.5 Illustration of Closed-Loop Procedure with Adjusted Technology Split, Net Inflow

In this example, the inflow of recovered material from the pool is MR_1 = 0.70 t and the export to the pool is MR_2 = 0.35 t. Hence, there is a net import of recovered material from the pool (i.e., $MR_1 > MR_2$). When applying the closed-loop procedure by adjusted technology split, the product system is allowed to use only as much recovered material as it generates (i.e., MR_1 is forced to be equal to MR_2 and $C_1 + R_1$ is forced to be equal to $C_2 + R_2$) and the remaining raw material requirements are fulfilled with virgin material ($V'm_2$), which may not reflect actual system behavior.

The related environmental loads are calculated as follows:

$$V'_2 = V \times (Rm_1 + Vm_2 - \beta_2 Rm_2)$$

Assuming $\beta_i = 1$ (i.e., 1.00 t of virgin pulp compensates for 1.00 t of de-inked pulp):

$$V'_2 = 500 \times (0.50\ t + 0.00\ t - 1 \times 0.25\ t) = 125\ kg\ CO_2E$$

The environmental load allocated to Pr_2 using the closed-loop procedure by adjusted technology split is calculated as follows:

$$E_{2,CL} = V'_2 + P_2 + U_2 + W_2 + C_2 + R_2 = 125 + 400 + 0 + 150 + 3.5 + 100 = 779\ kg\ CO_2E$$
$$= 1557\ kg\ CO_2E/t\ Pr_2$$

6.2.2.3 *Case 2b – Net Outflow: Similar Processes*

As mentioned in Section 6.2.2, the second case is when there is a net inflow or outflow of recovered material from the material pool, the virgin and recovered material processing are either identical or not very different in the studied product system and in the rest of the recovered material market, and the inherent properties of the virgin and recycled products are identical or similar. The case described here focuses on net outflows of recovered material. While in theory, a closed-loop procedure cannot be applied to study end-of-life recycling of virgin paper because the virgin system delivers material to a recovered fiber pool but does not take any recovered fiber back in, the virgin paper system can act as a good example to illustrate Case 2b, where there are net outflows of recovered material.

In this example (Figure 6.6), the inflow of recovered material from the pool is $MR_0 = 0$ t and the export to the pool is $MR_1 = 0.70$ t. Hence, there is a net export of recovered material to the pool. When applying the closed-loop procedure by technology adjustment, the product system is allowed to use as much recovered material as it generates (i.e., MR_0 is forced to be equal to MR_1 and $C_0 + R_0$ is forced to be equal to $C_2 + R_2$) and then to reduce its virgin material production accordingly.

The related environmental loads are calculated as follows:

$$V'_1 = V \times (Rm_0 + Vm_1 - \beta_1 Rm_1)$$

Assuming $\beta_i = 1$ (i.e., 1.00 t of virgin pulp compensates for 1.00 t of de-inked pulp):

$$V'_1 = 500 \times (0.00\ t + 1.00\ t - 1 \times 0.50\ t) = 250\ kg\ CO_2E$$

The environmental load allocated to Pr_1 using the closed-loop procedure with adjusted technology split is calculated as follows:

$$E_{1,CL} = V'_1 + P_1 + U_1 + W_1 + (C_1 + R_1) = 250 + 800 + 0 + 300 + 207 = 1557\ kg\ CO_2E$$
$$= 1557\ kg\ CO_2E/t\ Pr_1$$

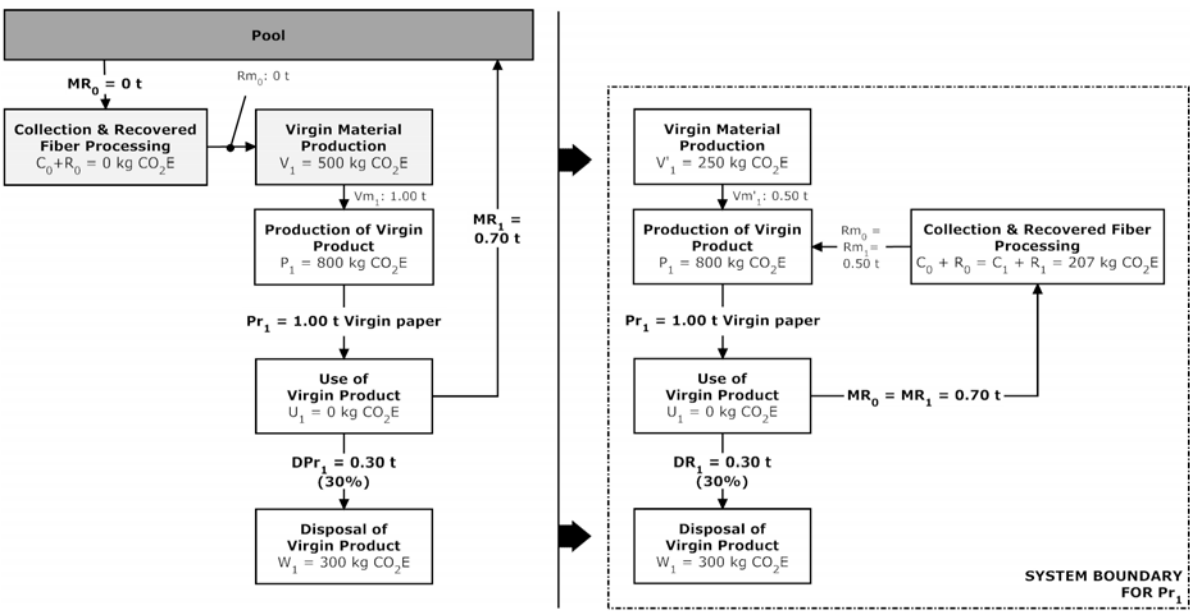


Figure 6.6 Illustration of Closed-Loop Procedure with Adjusted Technology Split, Net Outflow

As illustrated in this example, when using the closed-loop procedure with technology adjustment, the virgin and recycled products are assigned the same environmental load if they are recovered equally (given that there is no other difference in paper production or end-of-life).

Note: In this example, the closed-loop procedure gave the same result as the classical substitution method. This is because the closed-loop procedure was also applied to the virgin product. In theory, the closed-loop procedure is applicable to systems that both use material from the pool and provide material to the pool and hence it should *not* be applied to systems that do not use recovered materials. This is also why the closed-loop procedure is often described as an approximation of system expansion.

6.2.2.4 *Case 3 – Net Inflow or Net Outflow: Different Processes*

For cases where the processes for virgin and recovered material processing are different in the studied product system compared to those in the rest of the recovered material market, and/or the inherent properties of the virgin and recycled products are different, the closed-loop procedure is applied as before, except that the environmental loads of the various processes are adjusted to reflect these differences.

An example of this is presented in Figure 6.7. In this example, product Pr_2 sources recovered fiber from "Collection and Recovered Fiber Processing" that has environmental loads of C = 10 kg CO_2E/t CM_1 and R = 400 kg CO_2E/t Rm_1 (i.e., $C_1 + R_1$ = 207 kg CO_2E). This product then supplies recovered material to a pool and this material is subsequently used to make other products. The collection and recycling processes for those subsequent uses have environmental loads of C' = 20 kg CO_2E/t CM_i and R' = 600 kg CO_2E/t Rm_2 (i.e., $C'_2 + R'_2$ = 157 kg CO_2E). The closed-loop procedure demonstrated above would assume that the collection and recycling processes with loads of C'_2 and R'_2 (calculated using loads of C' and R') are used to produce the recycled fiber going into Pr_2. However, the processes actually used to produce that fiber have loads of C and R so the assumption would be incorrect. To account for the difference (between R and R', and C and C' in this example), the application of the closed-loop procedure should be modified by using a recovered fiber process within the system boundary that also has an environmental load of C = 10 kg CO_2E/t CM_1 and R = 400 kg CO_2E/t Rm_2 (i.e., $C_2 + R_2$ = 103.5 kg CO_2E).

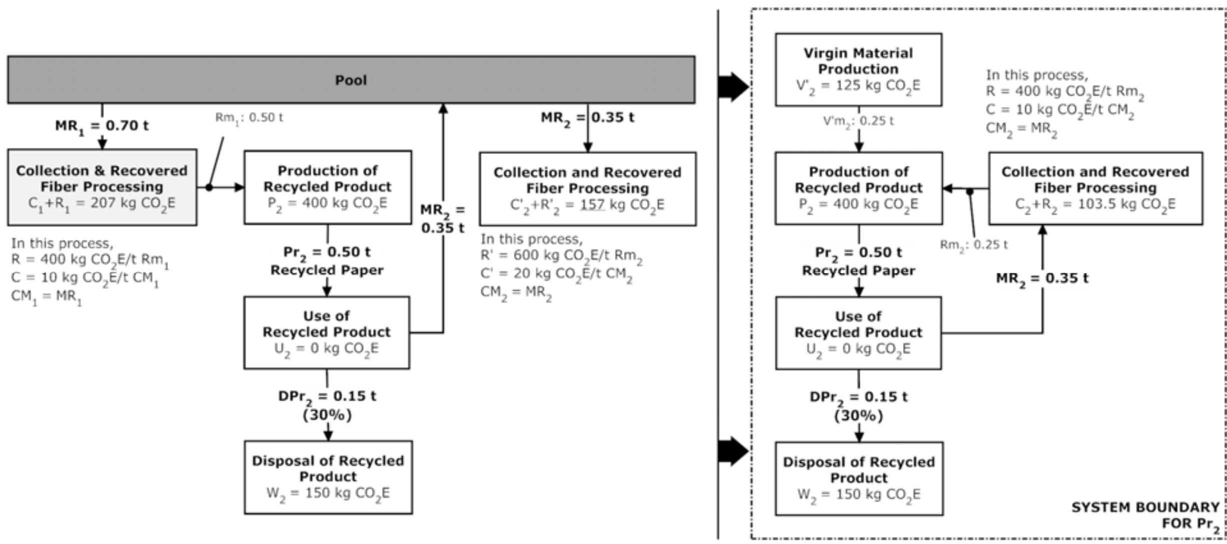


Figure 6.7 Example of Net Inflow with Different Recovery Processes in the Context of Applying the Closed-Loop Procedure

6.2.2.5 *Discussion of the Method*

The main feature of the closed-loop procedure is that the need for allocation is eliminated by assuming that the use of recovered material displaces the use of virgin material without requiring a lot of information on the other products in the material life cycle.

Some authors (Baumann and Tillman 2004; Ekvall 1999a; Tillman et al. 1994; Werner 2005) have argued that the closed-loop procedure is applicable in the following cases:

- where the material quality loss during recycling is small (i.e., recycled a large number of times);
- where the fraction of recovered material being collected for recycling from the product system is similar to the quantity of recovered material used in the product system; or

- where a material is recovered within the production of the same type of material (e.g., old newspapers are recovered for use in newsprint production or old corrugated containers are recovered for use in corrugated board production).

An assumption behind the closed-loop recycling procedure is that the recycled material is fully substitutable for virgin material. For instance, a ton of recycled pulp may be used in practice, in place of a ton of virgin pulp to produce paper, and the paper produced may fulfill the same function whether made of virgin or recycled fiber. However, in reality the virgin and recycled paper product may not be fully equivalent because their potential for further recycling is not the same given their average fiber length. In this case, assuming full substitution would not be adequate. Paper has been specifically described in the literature as a case for which the closed-loop recycling approximation is less suitable because recycling inherently results in fiber quality loss (Baumann and Tillman 2004). The ISO 14044 Standard requires that allocation methods be additive (mass balance requirement). That said, as noted by Werner (Werner 2005), the closed-loop procedure proposed by ISO is not additive because the virgin material production process is not fully accounted for.

6.2.3 *System Expansion*

ISO 14044 discusses "expanding the product system" as one means to avoid allocation. Two different models of system expansion have been distinguished in the literature (Azapagic and Clift 1999):

- one which expands the system boundary by fully accounting for the shared process/processes and redefines the functional unit and objective of the study to include the exported functions; and
- one which eliminates the exported functions by subtracting the processes that are substituted by these.

The former is often referred to as "direct system enlargement" and the latter as "substitution" or as the "avoided burden method."

Interpreted literally, "expanding the product system" as discussed in the ISO 14044 Standard fits better with the first model of system expansion presented above. There is no direct reference to the substitution method as a form of system expansion for the case of recycling in the ISO 14044 Standard. In the literature, it has been asserted that the substitution method is conceptually equivalent to the direct system enlargement method (European Commission 2010; Heijungs and Guinée 2007; Jungmeier et al. 2002; Weidema 2000; Werner 2005). A few models of the substitution method can be found in the literature, some of which are discussed in this report.

An early example of a model that applies a credit for end-of-life recycling was proposed by Fleisher (1994) and Karlsson (1994). The ISO 14049 Technical Report (ISO 2012b, Figure 16, p. 32) provides an example of *"open-loop with closed-loop recycling procedure [...] with expanded system boundaries"* which is very similar to this model of the substitution method. Similarly, it has been discussed in the literature that a model that uses a credit for the use of recovered material can also be applied in this situation (Ekvall 1996, 1999b). Another model found in the literature proposed that a systematic procedure can be used to determine whether and to what extent these credits should be applied (Ekvall and Weidema 2004). In all cases, however, the substitution method requires assumptions about potential interactions with other product systems and the uncertainty in these assumptions can impact the utility of the results.

Direct system enlargement and the three models of substitution described above are discussed next.

6.2.3.1 *Direct System Enlargement*

Direct system enlargement is what ISO 14044 (ISO 2006b) explicitly refers to as system expansion (Werner 2005). It consists of changing the objective of the study and the system boundary to include the co-products or their functions (Guinée et al. 2002; Richter, Werner, and Althaus 2006) or, in other words, of broadening the system boundary and introducing several functional units (Azapagic and Clift 1999). Because it consists of enlarging the system boundaries to incorporate the various different product made of the material, it can be described as an open-loop procedure.

Given the general model presented in Figure 5.1, the allocation equation for the environmental load from direct system enlargement, E_{DSE} is

$$E_{DSE} = \sum_{i=1}^{n} (V_i + P_i + U_i + W_i + C_i + R_i)$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, and R_i the environmental load of recovered fiber processing.

Note: For comparative LCA, direct system enlargement must be performed in a way that ensures that the compared systems are functionally equivalent. Procedures for doing this are available in the literature and are summarized under the discussion on the substitution method (see Section 6.2.3.5).

6.2.3.1.1 *Example*

Applying direct system enlargement to the pulp and paper example presented in Figure 5.1 means that the full life cycle of the fiber is included in the system boundary, as illustrated in Figure 6.8. The product system illustrated in Figure 6.8 now has more than one function: the function of the virgin product and the functions of the recycled products. The environmental load, E_{DSE}, of this product system can be calculated by summing up the individual environmental loads of each of the unit processes within the system boundary.

$$\begin{aligned} E_{DSE} &= V_1 + P_1 + U_1 + W_1 + C_1 + R_1 + V_2 + P_2 + U_2 + W_2 + C_2 + R_2 + Z \\ &= 500 + 800 + 0 + 300 + 7 + 200 + 0 + 400 + 0 + 150 + 3.5 + 100 + 653 \\ &= 3114\ kg\ CO_2E \end{aligned}$$

In this example, the functional unit needs to encompass

- 1.00 t of virgin paper (Pr_1); and
- 0.50 t (Pr_2) + 0.50 t ($\sum_{i=3}^{n} Pr_i$) of recycled paper.

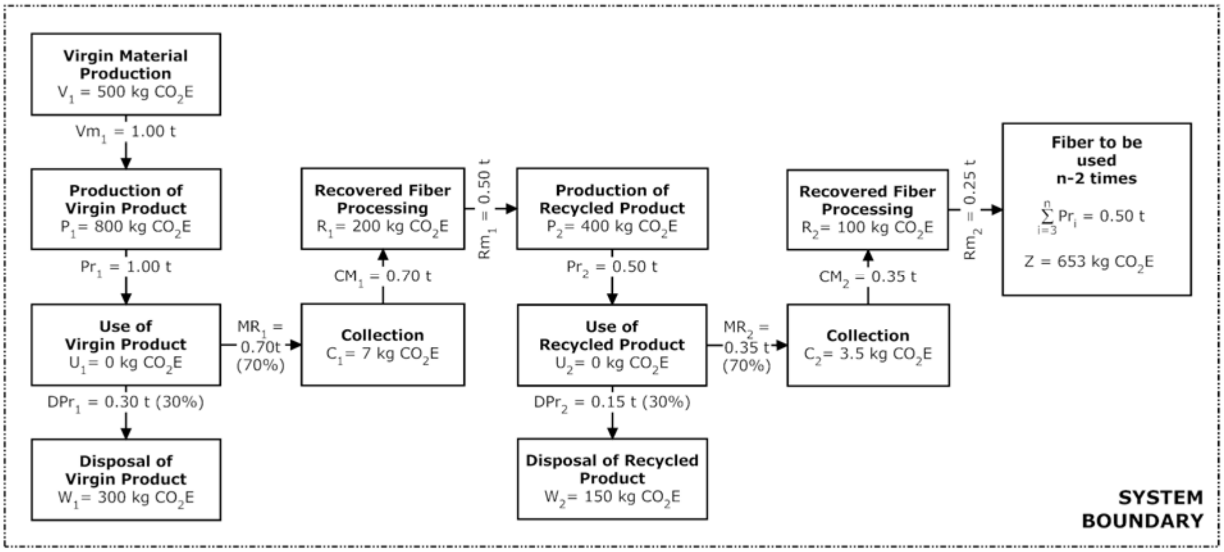


Figure 6.8 Application of Direct System Enlargement – Pulp and Paper Example

6.2.3.1.2 *Discussion of the Method*

Direct system enlargement deals with the open-loop allocation at the material life cycle level. While some pulp and paper case studies expand the system boundary to the whole fiber life cycle (see for instance (Byström and Lînnstedt 1997)), most of them expand the boundary only to the previous or next usage of the fiber. That is, direct system enlargement has most often been applied at the product life cycle level rather than at the material life cycle level, which seems more appropriate for input-output recycling problems than for cascade recycling problems. Using the material life cycle level is a more accurate model of the wood fiber system and is the only scientifically unambiguous solution to open-loop recycling allocation (Klöpffer 1996), but it introduces more uncertainty to the results of the analysis because it requires that the full fiber life cycle be modeled, which necessitates several assumptions. Using the product life cycle level requires much less information than accounting for the whole fiber life cycle but it provides less relevant information. Also, by limiting the scope of the analysis to the product life cycle level, there is a chance that the alternative production included is also a multifunction process, which would mean the allocation situation would effectively not be solved.

One of the main disadvantages of direct system enlargement is that because it provides an aggregated overall environmental load, it does not describe the separate environmental loads of the various products in the material (fiber) life cycle. In addition, changing the goal and scope of the study to include the additional functions may lead to inordinately large systems dominated by the added functions (Guinée et al. 2002).

Direct system enlargement is usually performed to maintain comparability of compared product systems by balancing a quantity of a co-product that occurs in only one of the product systems through adding an equivalent production in the other systems (Weidema 2000).

6.2.3.2 *Substitution – Credit for End-of-Life Recycling*

The substitution method, as applied in the literature, generally occurs at the product system level (Werner 2005). A recycling process is usually considered to provide two distinct functions: waste management for the upstream product system and secondary raw material production for the downstream product system. If the objective of the study is to calculate the environmental loads associated with the waste management function (or associated with the product being recovered), then the environmental load of the recycling process needs to be allocated between the two functions so that the loads associated with the studied function can be isolated. The credit for end-of-life recycling method (Fleisher 1994; Karlsson 1994; Klöpffer 1996) consists of including the recycling processes within the boundary of the system supplying the recovered material and crediting the system by subtracting an alternate material production process (almost always assumed to be virgin material). The ISO 14049 Technical Report (ISO 2012b, Figure 16, p. 32) provides an *"open-loop with closed-loop recycling procedure for aluminium package with expanded system boundaries"* which employs a very similar procedure. In this example, recovered aluminum packages are used in building material. The allocation situation is dealt with by expanding the system boundary to include the recycling process and subtract the avoided virgin aluminum production.

There is mention in the literature that the credit for end-of-life recycling method can be applied as long as the recycled material competes with other alternate materials and that data can be obtained for these (Ekvall 1996, 1999b). Modeling the environmental load of the alternate material production process can involve a large number of assumptions, however, and *if the uncertainty is high, the approach will not provide useful information* (Ekvall and Finnveden 2001, Weidema 2000).

To preserve mass balances when this method is applied, the product produced with recovered material should be allocated an environmental load equivalent to the environmental load of producing that product from virgin material and should not be allocated the recycling process.

Considering the simplified recycling model provided in Figure 5.1, the general equation for calculating the environmental load using a credit for end-of-life recycling for recycling, $E_{i,CR1}$, is

$$E_{i,CR1} = V'_i + V_i + P_i + U_i + W_i + C_i + R_i - V'_{i+1}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and V'_i is the virgin material production avoided because of recycling and is calculated as follows:

$$V'_i = V \times \beta_i Rm_{i-1}$$

β_i is an equivalency factor between virgin and recycled material (e.g., in this case, the quantity of virgin pulp equivalent to the quantity of recovered pulp).

6.2.3.2.1 *Example*

The application of the classical substitution model to the example provided in Figure 5.1 is described in this section and shown in Figure 6.9. The environmental load allocated to both products is calculated as follows:

$$E_{1,CR1} = V'_1 + V_1 + P_1 + U_1 + W_1 + C_1 + R_1 - V'_2$$

$$E_{2,CR2} = V'_2 + V_2 + P_2 + U_2 + W_2 + C_2 + R_2 - V'_3$$

Assuming $\beta_i = 1$ (i.e., 1.00 t of virgin pulp compensates for 1.00 t of de-inked pulp), then:

$$V'_1 = V \times \beta_1 Rm_0 = 500 \times 1 \times 0 = 0\ kg\ CO_2E$$

$$V'_2 = V \times \beta_2 Rm_1 = 500 \times 1 \times 0.50\ t = 250\ kg\ CO_2E$$

$$V'_3 = V \times \beta_3 Rm_2 = 500 \times 1 \times 0.25\ t = 125\ kg\ CO_2E$$

$Rm_0 = 0$ t, because no recovered fiber is used in the virgin product and $V_2 = 0$ t because no virgin fiber is used in the recycled product. Then,

$$E_{1,CR2} = V'_1 + V_1 + P_1 + U_1 + W_1 + C_1 + R_1 - V'_2 = 0 + 500 + 800 + 0 + 300 + 7 + 200 - 250 = 1557\ kg\ CO_2E = 1557\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,CR2} = V'_2 + V_2 + P_2 + U_2 + W_2 + C_2 + R_2 - V'_3 = 250 + 0 + 400 + 0 + 150 + 3.5 + 100 - 125 = 778.5\ kg\ CO_2E = 1557\ kg\ CO_2E/t\ Pr_2$$

As illustrated by this example, the first two products are allocated the same environmental load per unit of product irrespective of whether it was made from virgin or recovered material. This is true only because the recovery rate of the two products is the same[7]. The reason behind this result is that this method assumes that disposing of the product from virgin material will result in the same future environmental load that would result from disposing of the recovered material. In practice, virgin paper products are of greater "quality"[8] than recycled products, which means that this assumption is not fully valid. Also, this method gives the exact same result as does the closed loop approximation if the virgin and recovered material processing is identical in the studied product system and in the rest of the recovered material market.

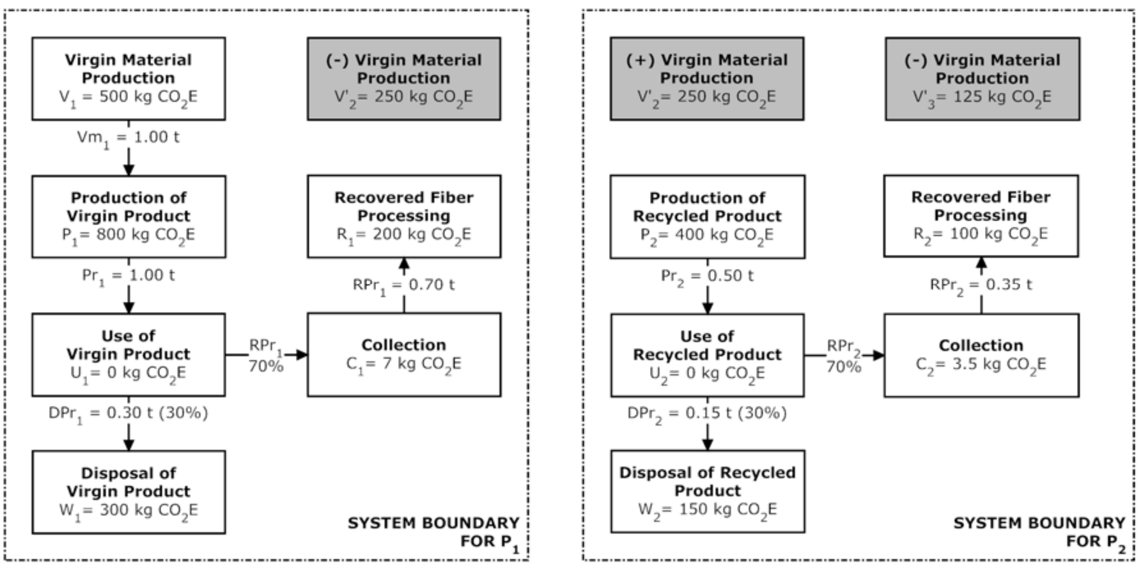


Figure 6.9 Application of the Credit for End-of-Life Recycling Method – Pulp and Paper Example [The affected processes are shown in dark gray in this figure.]

[7] The environmental load of the third to nth products is not the same because the nth product is not recovered.
[8] In terms of fiber length or, in other words, potential for future recycling.

A comparison between the credit for recycling (Figure 6.9) and the closed-loop procedure (Figure 6.5) is shown in Figure 6.10. This figure shows that the two methods treat recovery in a slightly different way. The closed-loop approach does not fulfill the mass balance requirement because an unlimited reuse of the material makes attributing the environmental load of virgin material production irrelevant (Werner 2005). In this example, depending upon the approach, there can be a 100% difference in calculated environmental load for virgin and recycled products.

	Virgin Product →	Recycled Product →	End-of-life	Total
Actual environmental load	$E_{1,AC} = 20$	$E_{2,AC} = 10$	$W_{AC} = 5$	35
Environmental load if virgin product is not recovered	$E_{1,WR} = 20$	$E_{2,WR} = 20$	$W_{WR} = 5$	45
Allocated environmental load – Credit for recycling	$E_{1,WR} – E_{2,WR} + E_{2,AC} = 10$	$E_{2,WR} – W_{AC} + W_{WR} = 20$	$W_{WR} = 5$	35
Allocated environmental load – Closed loop	$E_{2,AC} = 10$	$E_{2,AC} = 10$	$W_{WR} = 5$	25

Figure 6.10 Comparison of the Closed-Loop and Credit for End-of-Life Recycling Methods [In this example, AC is "actual" and WR is "without recovery."]

6.2.3.3 *Substitution – Credit for Use of Recovered Material*

A recycling process is usually considered to provide two functions: waste management for the upstream product system and secondary raw material production for the downstream product system. Likewise, a system using recovered paper to make new "recycled" paper products can be assumed to perform two functions. The first is the function performed by the "recycled products" themselves while the second is a waste management function for the upstream system that produced the used paper. If the objective of the study is to calculate the environmental loads associated with the function performed by the recycled product, the environmental load of the recycling process needs to be allocated between the two functions so that the loads associated with the function of the recycled product or of raw material production can be isolated. Similar to crediting the product system for end-of-life recycling, in this case the substitution method consists of including the recycling processes in the system boundary of the product using the recovered material and crediting the product system by subtracting an avoided waste management process. This can be done only if data can be obtained for the alternate fate of the material (Ekvall 1996, 1999b). Modeling the environmental load of the alternate waste management production process can involve a large number of assumptions and *if the uncertainty is high, the approach will not provide useful information* (Ekvall and Finnveden 2001; Weidema 2000).

To preserve mass balances, the product supplying the recovered material should be allocated the additional waste management that would occur if the material were not recovered and should not be allocated the recycling process.

Considering the simplified recycling model provided in Figure 5.1, the general equation for calculating the environmental load using a credit for use of recovered material, $E_{i,CR2}$, is

$$E_{i,CR2} = C_{i-1} + R_{i-1} - W'_{i-1} + V_i + P_i + U_i + W_i + W'_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and W'_i is the waste management avoided because of the use of recovered material. It is calculated as follows:

$$W'_i = W \times MR_i$$

where W is the unit environmental load of disposal processes (in kg CO_2E/t DPr_i), DPr_i is the quantity of product i to disposal and MR_i the quantity of used product i for recovery.

6.2.3.3.1 *Example*

The application of the credit for use of recovered material to the example provided in Figure 5.1 is described in this section and shown in Figure 6.11. The environmental load allocated to both products is calculated as follows:

$$W'_0 = 0$$

$$W'_1 = W \times MR_1 = 1000 \times 0.7 = 700\ kg\ CO_2E$$

$$W'_2 = W \times MR_2 = 1000 \times 0.35 = 350\ kg\ CO_2E$$

$$E_{1,CR2} = C_0 + R_0 - W'_0 + V_1 + P_1 + U_1 + W_1 + W'_1 = 0 + 0 - 0 + 500 + 800 + 300 + 700$$
$$= 2300\ kg\ CO_2E = 2300\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,CR2} = C_1 + R_1 - W'_1 + V_2 + P_2 + U_2 + W_2 + W'_2 = 7 + 200 - 700 + 0 + 400 + 150 + 350$$
$$= 407\ kg\ CO_2E = 814\ kg\ CO_2E/t\ Pr_2$$

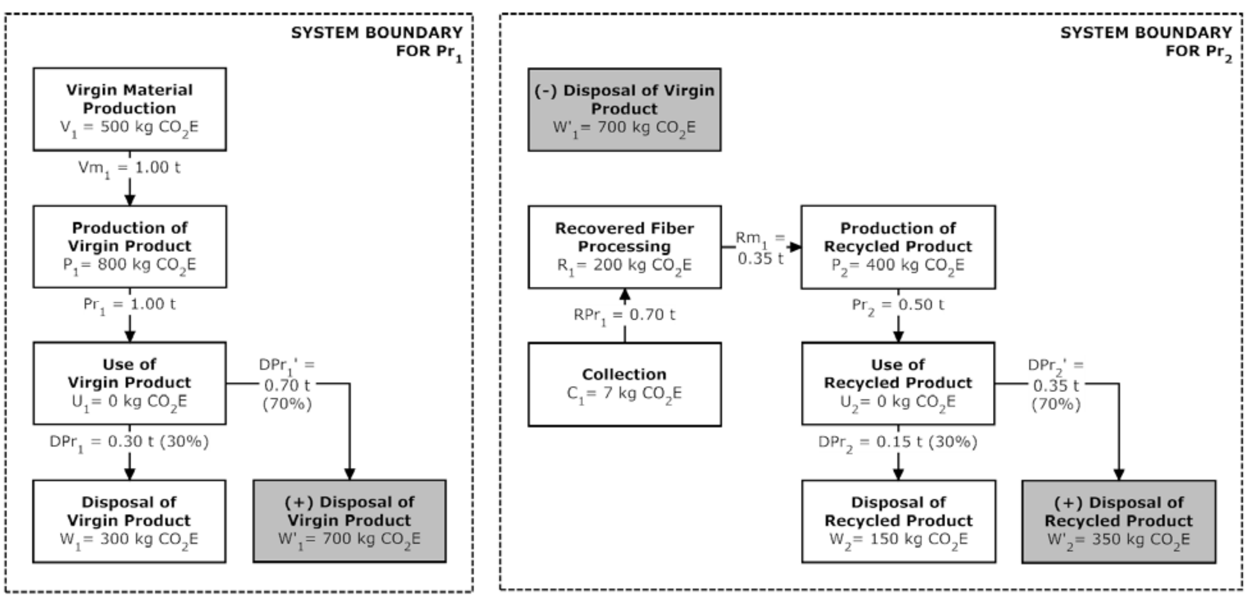


Figure 6.11 Application of the Credit for Use of Recovered Material Method – Pulp and Paper Example [The affected processes are shown in dark gray in this figure.]

6.2.3.4 *Discussion of the Crediting Methods*

The credit for end-of-life recycling method has been extensively applied to LCA studies of paper recycling as an end-of-life management option (NCASI 2009). Studies which award the credits for use of recovered material, however, are less common.

Frischknecht (2010) compared the end-of-life recycling method with the cut-off method (presented in Section 6.3.5.1 of this document). He argues that the credit for end-of-life recycling is more aligned with what has been termed the "weak sustainability concept," defined by Neumayer (Neumayer 2003), where natural capital can be substituted by man-made capital. He also describes this method as a risk-tolerant method because it grants credits to material recycling that may occur in the future assuming that the material will still be in demand by that time in the future. The same argument would be applicable to any method that somehow grants the studied product system with some benefits due to end-of-life recovery for recycling, for instance other substitution methods (see Section 6.2.3.5), the economic allocation method for pseudo-recycling (described in Section 6.3.3.3), or the number of uses method (described in Section 6.3.4). Interestingly, this argument may be less relevant when considering products with relatively short life spans and constant or increasing rates of recycling, such as paper.

There are several limitations for both methods (credit for end-of-life recycling and credit for use of recovered material). First, the credit for end-of-life recycling method was originally designed and intended for the development of recyclable products and it is not well suited for other types of decisions such as deciding between a product made from virgin or recovered material (Karlsson 1994). It has been argued that the crediting methods are often applied without consideration of their original intent, and thus may be based on inaccurate assumptions, both regarding the materials replaced by outflows of recovered material from the investigated product, and regarding the alternative fate of inflows of recovered material within the system boundaries, and that they do not provide a comprehensive picture of the implications of recycling (Ekvall 1996, 1999a, 2000). The uncertainty related to the determination of affected processes is inherent to the substitution method and may be of major importance (Weidema 2000). The uncertainty is even more important if there are several different possible scenarios regarding processes that may be substituted. It was argued that in cases where the uncertainty regarding the substituted processes is too high, the substitution approach would not provide useful information (Ekvall and Finnveden 2001; Weidema 2000).

The substitution method can make the process of data collection much more complicated, especially in cases where there is a need for further system expansion if the avoided processes are also shared between more than one product systems (Azapagic and Clift 1999; Curran 2006). Data availability as well as time and effort to collect this information can put the practicality of applying the substitution method into question (Curran 2006).

The crediting methods provide a mathematically simple way to eliminate the exported functions. Unfortunately, however, while easy to use, these methods are often applied in ways that result in internal inconsistencies (Guinée et al. 2002). This can happen if one of the two methods is not applied consistently to both the end-of-life recycling and to the use of recovered material, or if the two methods are employed simultaneously. Indeed, as illustrated in Figure 6.12, it is sometimes recommended that the substitution method be applied by fully accounting for the multifunctional system and eliminating the surplus functions by subtracting equivalent mono-functional systems to obtain a mono-functional functional unit (e.g., Azapagic and Clift 1999; Finnveden 1994; Tillman et al. 1994; Werner 2005).

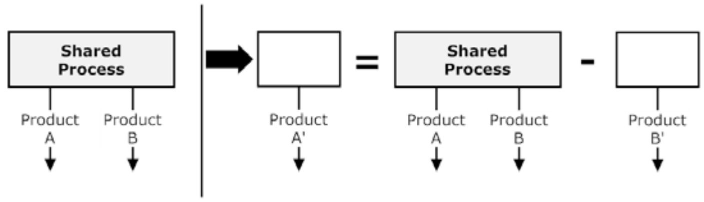


Figure 6.12 Schematic Illustration of Applying the Substitution Method as a Purely Mathematical Solution to Allocation

In these cases, the mass balance requirement will not be respected. The shared process will be included in both systems using it, which cannot be additive (Ekvall 1994; Heijungs and Guinée 2007). This is illustrated in Figure 6.13.

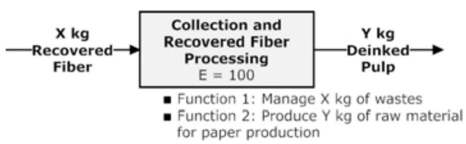
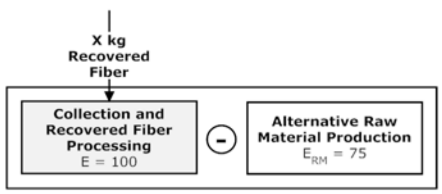
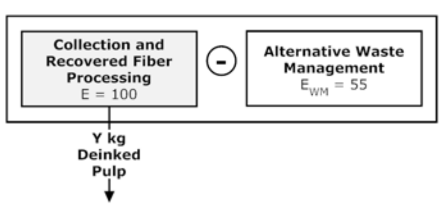
<table>
<tr><td>
</td><td>In this example, the process for collection and recovered fiber processing provides two functions: one related to waste management, and one related to the production of raw material for paper production. The total load of this process is, for instance, 100.</td></tr>
<tr><td>
</td><td>Case A: The waste management function is of interest for the study.
If the substitution method is applied as a purely mathematical solution to allocation, then the shared process is included in the boundary of the study and an alternative raw material production ($E_{RM} = 75$), is subtracted from the system boundary. Hence the load from the shared process that is allocated to the system of interest, the waste management function, E_A, is calculated as follows:
$E_A = E - E_{RM} = 25$</td></tr>
<tr><td>
</td><td>Case B: The raw material production function is of interest for the study.
If the substitution method is applied as a purely mathematical solution to allocation, then the shared process is included in the boundary of the study and an alternative waste management process ($E_{WM} = 55$), is subtracted from the system boundary. Hence the load from the shared process that is allocated to the system of interest, the raw material production function, E_B, is calculated as follows:
$E_B = E - E_{WM} = 45$</td></tr>
<tr><td colspan="2">The ISO 14044 (ISO 2006b, p. 14) requires that “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” (i.e., mass balance requirement). This means that E shall be equal to $E_A + E_B$.
For this example:
$E = 100, E_A = 25, E_B = 45$
$E_A + E_B = 70 \neq 100$
This illustrates how the application of the substitution method as a mathematical solution to allocation can lead to violation of the ISO mass balance requirement. This requirement is also violated in cases where what is credited on one side is not added back on the other side.</td></tr>
</table>

Figure 6.13 Mass Balance Problem Occurring When the Substitution Method Is Applied as a Purely Mathematical Solution to Allocation: An Example

As mentioned previously, the ISO standard requires that 1) a similar allocation procedure is applied to the inflows and outflows of recovered material, and 2) that the allocation procedure is additive (mass balance requirement). This would mean that, in order to be compliant with the ISO standard, application of a credit to both the inflow and outflow of recovered material would be required. However, as shown in the previous example, this is likely to violate the mass balance requirement unless a decision is made regarding the allocation of the recycling process.

6.2.3.5 *Substitution – Ekvall (2000)*

This section discusses a procedure that has been proposed in the literature to deal with some of the limitations of the crediting methods discussed above (Ekvall 2000; Ekvall and Weidema 2004). Like the crediting methods above, this variation on the substitution method for allocation is not discussed in ISO standards. This proposed approach is intended to address open-loop recycling allocation situations, i.e., situations where material is recovered from the investigated system (outflows of recovered/recycled material) or when recovered/recycled material is used in the studied product system (inflows of recovered/recycled material). The substitution method proposed by Ekvall and Weidema (Ekvall and Weidema 2004) involves the expansion of the system boundary to include (by addition or subtraction) the unit processes that are actually affected by the inflows and outflows of recovered material. As for the credit for end-of life recovery, this method can be described as a risk-tolerant method because it grants credits to material recycling that may occur in the future assuming that the material will still be in demand by that time in the future. This is more in line with change-oriented LCAs, which was the original intent of Ekvall's and Weidema's method. However, this method has also been used in accounting LCAs.

As discussed previously, the default assumption concerning outflows of recovered material when applying the classical substitution method is that they produce a reduction of virgin material production in another product system (Ekvall 1996, 1999a; Ekvall and Finnveden 2001). This is also what is suggested in the ISO 14049 Technical Report (ISO 2012b). This assumption may be adequate if the objective of the study is to assess the effect of increasing the global recovery rate but is not adequate if the objective is to provide information on a specific product system (Ekvall and Finnveden 2001). In practice, the outflow of recovered material may also displace recovered material from other sources, or it may compete with other types of material (e.g., recovered fiber can compete with plastic).

In cases of recovered fiber inflows, expanding the system boundaries means including the alternative usage of the recovered material if it were not used in the studied system. A default assumption is that it would be disposed of (Ekvall 1996, 1999a). In practice, the recovered material could also be used in other recycled products that would otherwise have to compensate with virgin material.

Material replaced by outflows of recovered/recycled material and alternative fate of inflows of recovered material can be difficult to identify but both may be critical to LCA results.

If the uncertainty regarding the avoided material production or the alternative fate of inflows of recovered material is high, the avoided burden approach may not provide useful information (Ekvall and Finnveden 2001; Weidema 2000).

In order to render the substitution method proposed by Ekvall and Weidema (2004) operational, the authors also proposed some simplifications. One simplification is to assume that recycled material only competes with virgin or recycled material of the same type. Even with this simplification it is still necessary to establish the extent to which recovered/recycled material from the studied product system displaces virgin material versus recycled material in other product systems and to what extent the use of recycled material in the studied system results in reduced waste management versus use of recycled material in other product systems. In this context, an approach based on price elasticities has been proposed in the literature (Ekvall 2000; Ekvall and Weidema 2004). The original method proposed by Ekvall (2000) requires information on market behavior that may be difficult or even impossible to obtain.

Also, price elasticities strongly depend on the time horizon for the study, meaning that it would be necessary to determine elasticities for each specific case studied. Because this is not very practical further simplification is needed. Some options for further simplification are (Ekvall and Weidema 2004)

- use default values if available;
- assume that the supply or the demand is fully elastic; or
- assume that 50% of an outflow of recovered material from the life cycle studied replaces virgin material and that the remaining 50% replaces recycled material from other sources, and that inflow of recovered material results in 50% increased collection and 50% reduced use of cascade material in other products (50/50 approximation).

The 50/50 approximation minimizes the maximum error that can be made and does not necessitate that default elasticities be available. An inherent assumption is that there is demand for and sufficient supply of recovered material so that recycling can occur.

Originally, this system expansion approach was developed as a direct system enlargement method with the objective of analyzing changes in the recovered material flows (i.e., for change-oriented LCAs). However, the authors also proposed a version that is suitable for accounting LCAs, which they referred to as the "allocation approximation." Using this approximation, the recovered material (i.e., material after collection for recycling) is attributed a general environmental load, M_i, of

$$M_i = -\alpha(R_i - V'_{i+1}) + (1-\alpha)(C_i - W'_i)$$

where

$$V'_i = V \times \beta_i Rm_{i-1}$$

$$W'_i = W \times MR_i$$

R_i is the environmental load of recovered fiber processing, C_i the environmental load of collection of used product, Rm_i is the quantity of recycled material from product i, β_i is an equivalency factor between virgin and recycled material (e.g., in this case the quantity of virgin pulp equivalent to a given quantity of recovered pulp to be suitable for the same product),V is the environmental load of virgin pulp production per ton of virgin pulp (see Figure 5.1), and α is a constant that depends on market conditions.

If the 50/50 approximation is applied, then α is equal to 0.5. If the supply of recovered material is fully elastic, then α is equal to 1.

M_i is added to systems using recovered material and subtracted from the system generating the recovered material.

Hence the general equation for the environmental load calculated using the 50/50 allocation approximation, $E_{i,50/50AA}$, is

$$E_{i,50/50AA} = M_{i-1} + R_{i-1} + V_i + P_i + U_i + W_i + C_i - M_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, and R_i the environmental load of recovered fiber processing.

More information on how these equations have been obtained, and on the assumptions behind these, can be found in Ekvall and Weidema (2004).

6.2.3.5.1 *Example*

In this section, the 50/50 allocation approximation is illustrated using the example presented in Figure 5.1.

The environmental load of the recovered fiber can be calculated as follows:

$$M_1 = -0.5(R_1 - V'_2) + (1 - 0.5)(C_1 - W'_1)$$

$$M_2 = -0.5(R_2 - V'_3) + (1 - 0.5)(C_2 - W'_2)$$

Assuming $\beta_i = 1$ (i.e., 1.00 t of virgin pulp compensates for 1.00 t of de-inked pulp), then:

$$V'_2 = V \times \beta_2 Rm_1 = 500 \times 1 \times 0.50\ t = 250\ kg\ CO_2E$$

$$V'_3 = V \times \beta_3 Rm_2 = 500 \times 1 \times 0.25\ t = 125\ kg\ CO_2E$$

$$W'_1 = W \times MR_1 = 1000 \times 0.70 = 700\ kg\ CO_2E$$

$$W'_2 = W \times MR_2 = 1000 \times 0.35 = 350\ kg\ CO_2E$$

and

$$M_1 = -0.5(200 - 250) + (1 - 0.5)(7 - 700) = -322\ kg\ CO_2E$$

$$M_2 = -0.5(100 - 125) + (1 - 0.5)(3.5 - 350) = -161\ kg\ CO_2E$$

The environmental load of each product is then calculated as follows:

$$\begin{aligned} E_{1,50/50AA} &= M_0 + R_0 + V_1 + P_1 + U_1 + W_1 + C_1 - M_1 \\ &= 0 + 0 + 500 + 800 + 0 + 300 + 7 - (-322) = 1929\ kg\ CO_2E \\ &= 1929\ kg\ CO_2E/t\ Pr_1 \end{aligned}$$

$$\begin{aligned} E_{2,50/50AA} &= M_1 + R_1 + V_2 + P_2 + U_2 + W_2 + C_2 - M_2 = \\ &= -322 + 200 + 0 + 400 + 0 + 150 + 3.5 - (-161) = 593\ kg\ CO_2E \\ &= 1186\ kg\ CO_2E/t\ Pr_2 \end{aligned}$$

6.2.3.6 *Summary Discussion of System Expansion Methods*

Based on the literature, the main advantage of any form of system expansion, be it direct system enlargement or substitution, is the modeling of the indirect effects of a product system on other product systems, thereby providing a more comprehensive picture of the effects of the material life cycle (Azapagic and Clift 1999; Ekvall 1999a, 2000; Ekvall and Weidema 2004). However, it increases the complexity of the study, requires additional data and adds uncertainty to the LCA results because of the simplifications that have to be performed in order for the method to be practical (Azapagic and Clift

1999; Ekvall 1996, 1999a; Guinée et al. 2002; Tillman et al. 1994). In some cases, the redefined product system can be dominated by the environmental load of the added/subtracted processes and there is a risk that the environmental load of the system under study will be seen as minor and become "lost" (Azapagic and Clift 1999; European Commission 2010; Finnveden 1994; Guinée et al. 2002; Strömberg et al. 1997). This can lead to results showing negative emissions and impacts that are less than zero (for substitution methods), results that can easily be misinterpreted. In this case, there is a need for special attention in reporting of results. For instance, the environmental load directly attributable to the system under study and from other systems could be reported separately.

Crediting methods generally consider only the interactions between two connected life cycles, without fully investigating how a change in the market propagates in the material life cycle (Werner 2005). One reason for this is that substitution methods generally assume that recycled material is fully substitutable for virgin material (e.g., one ton of recycled pulp is fully substitutable for one ton of recycled pulp). In reality, a product made of recycled material will not be fully equivalent to a product made from virgin material if their potential for further recycling is not the same (see discussion of inherent properties in Section 6.2.2). Defining a true substitution ratio is difficult (Werner 2005). For instance, if some paper is diverted from disposal, more than one recycling loop will occur. Furthermore, if recovered paper is diverted from one usage to another without affecting the recovery rate, this will also have an effect on the number of times a fiber can be reused (e.g., if recovered paper is recycled into containerboard, it will be possible to recycle it more times than if reused in tissue paper). Diverting a virgin paper product will not have the exact same effect as diverting a paper product that already contains recycled fiber if the whole material life cycle is considered. Also, the credit for end-of-life recycling has been described as a risk-tolerant method because it results in the postponing of the accounting of some environmental load in the future (Frischknecht 2010). The same reasoning can also partly apply to the substitution method proposed by Ekvall (2000).

The direct system enlargement approach and the substitution approach include in the framework of analysis the effects that the studied system potentially has on other product systems. The direct enlargement approach, however, does not generate information on the environmental load that is specific to a given function. The substitution method has been suggested as a means of generating information on a single function of interest (Ekvall 1996, 2000; Ekvall and Finnveden 2001; Ekvall and Tillman 1997; Ekvall and Weidema 2004; Finnveden and Ekvall 1998). That said, application of the substitution method can lead to violations of the ISO mass balance requirement, i.e., mass conservation, if not applied correctly.

6.3 Partitioning Methods

As mentioned previously, the ISO 14044 Standard (ISO 2006b) specifies that the hierarchy for co-product allocation also applies to recycling. This means that underlying physical relationships should be favored over other relationships to perform allocation wherever it is not possible to avoid allocation. Underlying physical relationships are relationships that reflect the way in which the environmental loads are changed by quantitative changes in the products or functions delivered by the product system. In cases where allocation based on an underlying physical relationship cannot be performed, then another relationship can be used.

The ISO 14044 Standard (ISO 2006b) also mentions that open-loop recycling allocation should be based, where feasible, on physical properties (e.g., mass), economic value (e.g., market value of the scrap material or recovered material in relation to market value of primary material), or the number of subsequent uses of the recovered material. None of these three options is based on underlying physical relationships.

Partitioning methods proposed in ISO 14044, as well as other methods that have been used in pulp and paper case studies, are discussed next.

6.3.1 *Underlying Physical Relationship*

No practical example of applying underlying physical relationships for partitioning can be readily found in the literature. Furthermore, it is often argued that in a material life cycle, the causal relationship between the functions of the various products and the environmental load of the material life cycle is economic rather than physical (Ekvall and Finnveden 2001). Therefore, this will not be discussed further.

6.3.2 *Other Relationship: Physical Properties (Mass)*

Allocation is often based on some physical quantity (e.g., mass) without reference to the underlying physical relationships involved (Finnveden 1994). Allocation based on mass for open-loop recycling problems makes sense only at the material life cycle level. In this case, the entire material life cycle is considered to be a multifunction process providing the functions of all products in the life cycle and the mass of the products can be used as the basis for allocation (Azapagic and Clift 1999; Boguski, Hunt, and Franklin 1994; Vigon et al. 1993). This method has also been described as the "open-loop recycling allocated system approach" (Curran 1996) or the quasi-co-product method (Axel Springer Verlag AG, Stora, and Canfor 1998). This is a form of system expansion, but allocation is not avoided. Pulp and paper case studies using this method can be found (Axel Springer Verlag AG, Stora, and Canfor 1998).

The general equations for calculating the environmental load using allocation based on mass, $E_{i,Mass}$, is

$$E_{i,Mass} = \frac{Pr_i}{\sum_{j=1}^{n} Pr_j} \sum_{j=1}^{n} \left(V_j + P_j + U_j + W_j + C_j + R_j\right)$$

where V_j is the environmental load of virgin material production used in product j, P_j the environmental load of the production of product j, U_j the environmental load of use of product j, W_j the environmental load of product j disposal, C_j the environmental load of collection of used product j, R_j the environmental load of recovered fiber processing, and Pr_j the quantity of product j.

6.3.2.1 *Example*

Using this method the environmental load of the entire material life cycle is split across the various products in proportion to the product mass. On a mass basis, all products are allocated the same environmental load. For the example presented in Figure 5.1, the environmental load of the products can be calculated as follows:

$$\begin{aligned} E_{2,Mass} &= \frac{Pr_2}{Pr_1 + Pr_2 + \sum_{j=3}^{n} Pr_j} (V_1 + P_1 + U_1 + W_1 + C_1 + R_1 + V_2 + P_2 + U_1 + W_2 + C_2 + R_2 + Z) \\ &= \frac{0.50}{1.00 + 0.50 + 0.50} (500 + 800 + 0 + 300 + 7 + 200 + 0 + 400 + 0 + 150 + 3.5 \\ &\quad + 100 + 653) = 779\ kg\ CO_2E = 1557\ kg\ CO_2E/t\ Pr_2 \end{aligned}$$

6.3.2.2 *Discussion of the Method*

According to the literature, the main advantages of this method are its relative simplicity and its acknowledgement of the relationships between the virgin and recycled products (because all products share in the system's overall loads), including the fact that the recycled product would not exist if the virgin product was not manufactured first (Boguski, Hunt, and Franklin 1994; Curran 1996). However, it does not take into account the market reactions to changes in inflows and outflows of recovered material from the studied product system (Ekvall and Finnveden 2001). It generally has the same disadvantages as the direct system enlargement method except that it provides environmental loads specific to each of the products.

6.3.3 *Other Relationship: Economic Value*

ISO 14044 specifies that allocation can be based the market value of the scrap material or recovered material in relation to market value of primary (virgin) material (i.e., allocation based on the economic value). This method, which has also been referred to as allocation based on social causation (Finnveden 1994), has not typically been used for paper recycling allocation, but examples of its application to other economic sectors can be found in the literature (Guinée et al. 2004; Jolliet, Saadâe, and Crettaz 2005).

In economic allocation the recycling process is considered to be a waste management process if the economic value of the recovered material is negative (Guinée et al. 2002; Guinée, Heijungs, and Huppes 2004; Werner 2005). This leads to multiple possible situations illustrated in Figure 6.14 and discussed in the next sections.

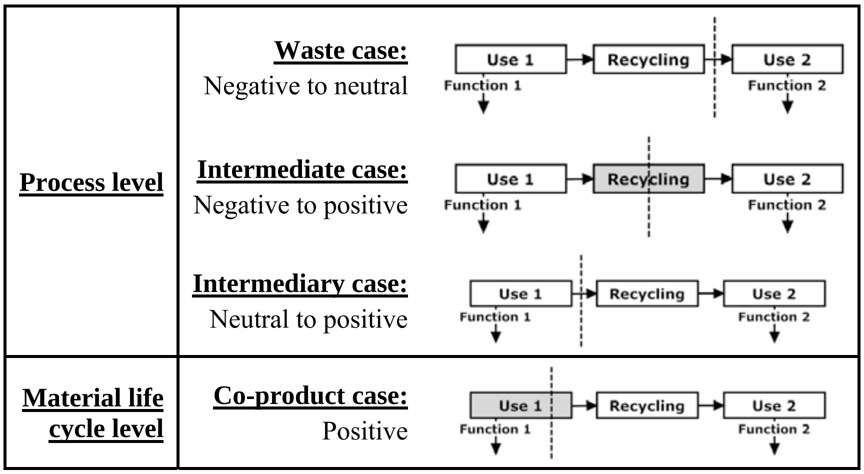


Figure 6.14 System Boundary and Allocation Based on the Economic Value of the Recovered Material (after Guinée et al. 2002; Guinée, Heijungs, and Huppes, 2004; and Werner 2005, modified) [In this figure the process that is considered to be shared is shown in gray and where the system boundary is set is depicted by a dashed vertical line.]

6.3.3.1 *Waste Case*

In this case, the scrap material has a negative economic value that will never become positive. That is, the system generating it has to pay to dispose of it (negative value) but the system using the recovered material does not pay to obtain it (neutral value) or is paid to accept it (negative value). In this case, the scrap material is truly a waste and is assigned no production-related environmental load. The system generating it assumes the environmental load related to the treatment of this waste and the material comes "free" of environmental load to the system using it. There is a need to evaluate at what point the scrap material enters the system boundaries of the product using it as recovered material in its production (i.e., the point at which the economic value of the material changes from negative to neutral, illustrated by a vertical dashed line in Figure 6.14). For instance, in the example illustrated in Figure 5.1, the switching point in the economic value could either be the "collection" process or the "recovered fiber processing" and hence, either could be considered as the waste treatment process. Also, in reality, recovered paper is almost never a true waste because the user generally pays for it, at least partially.

6.3.3.2 *Intermediate Case*

In this case, the system generating the scrap material either gives it away (neutral value) or has to pay to dispose of it (negative value) and the system using the recovered material has to pay to obtain it (positive value). A treatment process is required before the waste becomes a valuable product. It is thus necessary to determine the point at which the material goes from a neutral or negative economic value to a positive economic value. The process that constitutes the switching point in the economic value can be, for instance, the collection process or the recovery process. In the case where the collection process is the turning point the general equation for allocating the environmental load is

$$E_{i,EI,Coll} = (1-\rho_{i-1})C_{i-1} + R_{i-1} + V_i + P_i + U_i + W_i + \rho_i C_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing and

$$\rho_i = \frac{-EV_{i,MR}}{-EV_{i,MR} + EV_{i,CM}}$$

$EV_{i,MR}$ is the economic value of scrap material and $EV_{i,CM}$ is the economic value of the collected material. Note that the economic value of a material for which there are disposal costs is negative and the economic value of a material for which there are acquisition costs is positive. The economic value of material that is disposed of at no cost is zero.

If the process responsible for the change in the economic value of the material is the recovery process, then the environmental load is calculated as follows:

$$E_{i,EI,Rec} = (1-\rho_{i-1})R_{i-1} + V_i + P_i + U_i + W_i + C_i + \rho_i R_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing and

$$\rho_i = \frac{-EV_{i,CM}}{-EV_{i,CM} + EV_{i,Rm}}$$

where $EV_{i,Rm}$ is the total economic value of the recovered material and $EV_{i,CM}$ is the economic value of the collected material.

6.3.3.2.1 *Example*

If a pulp and paper producer pays for recovered paper that has been collected but it does not pay for the collection process, then economic allocation for intermediary cases can be applied. In this case, the switching point in the economic value of the waste is the collection process. Economic allocation is applied by dividing the environmental load of the collection process between the upstream and downstream product systems based on the cost of treatment versus the price paid by the user of the recovered material to obtain this material. This is illustrated in Figure 6.15. For this example, it is assumed that the user of paper pays \$10/t to dispose of it (i.e., $EV_{MR,1}$ = -\$10.00/t x 0.70 t = -\$7.00, $EV_{MR,2}$ = -\$10.00/t x 0.35 t = -\$3.50) and that the user of recovered paper pays \$90.00/t to acquire the raw material (i.e., $EV_{CM,1}$ = +\$90.00/t x 0.70 t = +\$63.00, $EV_{CM,2}$ = +\$90.00/t x 0.35 t = +\$31.50). The environmental load attributable to the first product in the material life cycle is calculated as follows:

$$E_{1,EI,Coll} = (1-\rho_0)C_0 + R_0 + V_1 + P_1 + U_1 + W_1 + \rho_1 C_1$$

In this equation, $\rho_0 = C_0 = R_0 = 0$, because the first product in the material life cycle does not use recovered fiber.

$$\rho_1 = \frac{-EV_{MR,1}}{-EV_{1,MR} + EV_{1,CM}} = \frac{-(-\$7.00)}{-(-\$7.00) + \$63.00} = 0.10$$

$$E_{1,EI,Coll} = 0 + 0 + 500 + 800 + 0 + 300 + 0.1 \times 7 = 1601\ kg\ CO_2E = 1601\ kg\ CO_2E/t\ Pr_1$$

The environmental load attributable to the recycled product is calculated as follows:

$$E_{2,EI,Coll} = (1-\rho_1)C_1 + R_1 + V_2 + P_2 + U_2 + W_2 + \rho_2 C_2$$

$$\rho_2 = \frac{-EV_{CM,2}}{-EV_{2,CM} + EV_{2,Rm}} = \frac{-(-\$3.50)}{(-\$3.50) + \$31.50} = 0.10$$

$$\begin{aligned} \mathrm{E_{2,EI,Coll}} &= (1-0.1) \times 7 + 200 + 0 + 400 + 0 + 150 + 0.10 \times 3.5 = 744\ \mathrm{kg\ CO_2} \\ &= 1487\ \mathrm{kg\ CO_2E/t}\ Pr_2 \end{aligned}$$

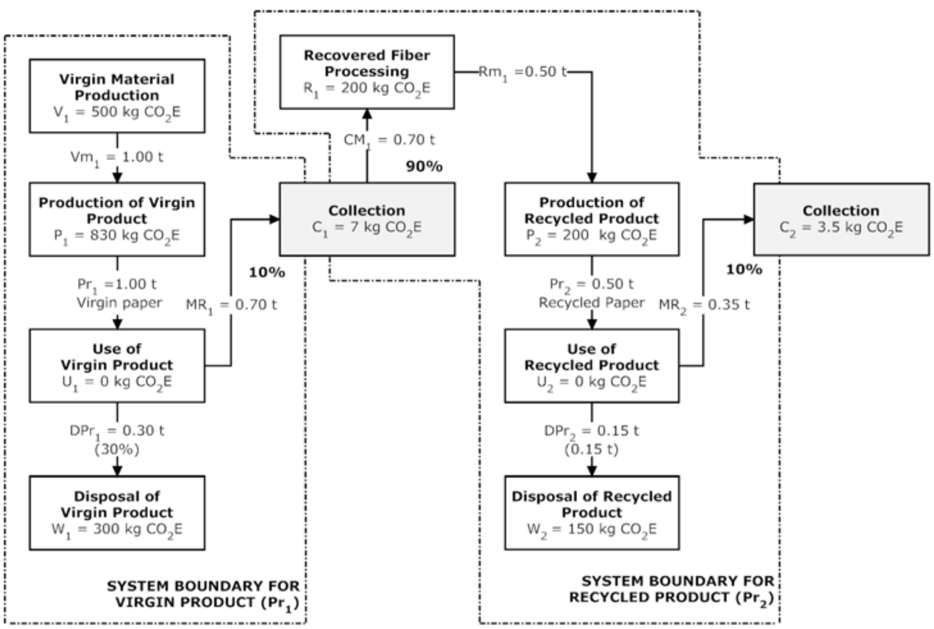


Figure 6.15 Example of Economic Allocation – Intermediate Case

6.3.3.3 *Co-Product Case*

6.3.3.3.1 *Overview of the Method*

The third economic allocation case is when the material is so valuable that it never has a negative or neutral value. In other words, it is a co-product rather than a waste. This happens if the downstream system pays to obtain it but there is no treatment cost associated with the material (or if the users of the recovered material pay for its treatment cost). This is referred to as "pseudo-recycling" in Guinée, Heijungs, and Huppes (2004).

In this case, the use process can be seen as a multifunctional process delivering two functional flows: the product that is being used and the material that is going to be recycled. The environmental load required to deliver these functions (i.e., the environmental load associated with the use process itself and of everything upstream) is split between the virgin product and the subsequent recycled products based on the economic value related to the two functions[9]. This is applied only to the fraction of the virgin product that is recovered for recycling. The collection and recovery processes are no longer multifunctional. The environmental loads using this approach can be calculated as follows:

$$E_{i,ECP} = \begin{cases} \dfrac{DPr_i}{Pr_i}(V_i + P_i + U_i) + A_{i,Eco}\dfrac{MR_i}{Pr_i}(V_i + P_i + U_i) + W_i, & i = 1 \\ A_{i,Eco}\dfrac{MR_i}{Pr_i}(V_1 + P_1 + U_1) + R_{i-1} + C_{i-1} + P_i + U_i + W_i, & 2 \le i \le n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, DPr_i the quantity of product i to disposal, MR_i the quantity of used product i for recovery, Pr_i the quantity of product I, and $A_{i,Eco}$ is the allocation factor for pseudo-recycling, which is calculated as follows:

$$A_{i,Eco} = \begin{cases} \dfrac{MR_1 \times EV_1}{MR_1 \times EV_1 + \sum_i^{n-1}(MR_i EV_i)}, & i = 1 \\ \dfrac{MR_{i-1}EV_{MR,i-1}}{\frac{MR_1}{Pr_1} \times EV_1 + \sum_i^{n-1}(MR_i EV_i)}, & 2 \le i \le n \end{cases}$$

EV_1 is the economic value of product i and $EV_{MR,i}$ is the economic value of the recovered product i (in $/unit).

Note: This equation is valid only for cases where V_2, V_3, …, and $V_n = 0$. In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system for which equations for recycled products (i>1) are applied.

[9] Only one example of application of this method was found in the literature. The example in question deals with the use of aluminum to produce an engine that is recycled into another aluminum product. The authors (Guinée, Heijungs, and Huppes 2004) used the economic value of using the engine and the economic value of the used engine as the basis for allocation. Note that the authors do not provide an explanation of how this would apply to cascade recycling.

6.3.3.3.2 *Example*

The pulp and paper example presented in Figure 5.1 is used to illustrate the economic allocation method for co-product cases and this is presented in Figure 6.16. In the example, 70% of the virgin product is recovered for recycling. To apply the economic allocation for co-product cases, the virgin product system (Pr_1) is first divided into two sub-systems:

- system for producing Pr_{1A}, which is equal to 30% (100% - 70%) of system Pr_1 but for which the product is fully disposed of i.e., $E_{1A} = V_{1A} + P_{1A} + U_{1A} + W_{1A} = 0.30(V_1 + P_1 + U_1) + W_1$; and
- system for producing Pr_{1B}, which is equal to 70% of system Pr_1 but for which the product is fully recovered i.e., $E_{1B} = V_{1B} + P_{1B} + U_{1B} = 0.70(V_1 + P_1 + U_1)$.

Then, the economic allocation for the co-product case can to be applied only to the system for producing Pr_{1B} i.e., to that portion of the product that is fully recovered. The following economic values are assumed.

- Economic value of virgin paper (EV_1) is $250/t.
- Economic value of the recovered paper ($EV_{MR,1} = EV_{MR,2} = \ldots = EV_{MR,n-1}$) is $150/t.

Using this information, the allocation factors for virgin material production are calculated as follows:

$$A_{1,Eco} = \frac{MR_1 \times EV_1}{MR_1 \times EV_1 + \sum_{i=1}^{n-1}(MR_i EV_i)} = \frac{0.7 \times 250}{0.7 \times 250 + 1.40 \times 150} = 0.45$$

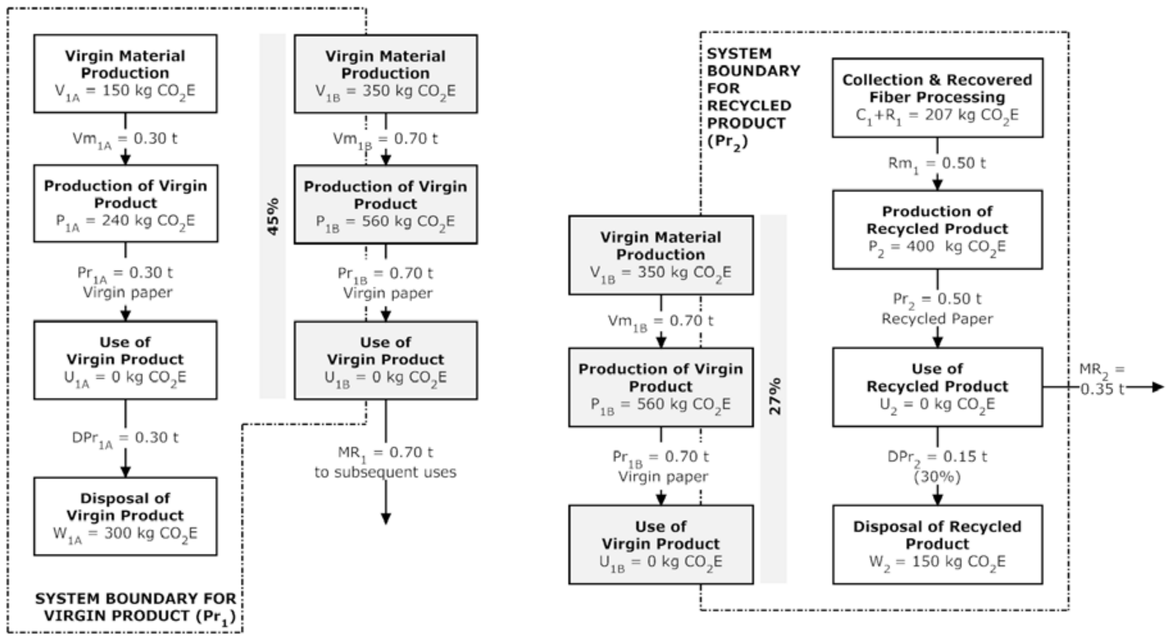
$$A_{2,Eco} = \frac{MR_{i-1} \times EV_{i-1}}{MR_1 \times EV_1 + \sum_{i=1}^{n-1}(MR_i EV_i)} = \frac{0.7 \times 150}{0.7 \times 250 + 1.40 \times 150} = 0.27$$

The remaining 28% allocation factor is applied to products 3 to n.

The environmental load of the individual product is calculated as follows:

$$\begin{aligned} E_{1,ECP} &= \frac{DPr_1}{Pr_1}(V_1 + P_1 + U_1) + A_{1,Eco}\frac{MR_1}{Pr_1}(V_1 + P_1 + U_1) + W_1 \\ &= \frac{0.30}{1.00}(500 + 800 + 0) + 0.45\frac{0.70}{1.00}(500 + 800 + 0) + 300 = 1104\ kg\ CO_2E \\ &= 1104\ kg\ CO_2E/t\ Pr_1 \end{aligned}$$

$$\begin{aligned} E_{2,ECP} &= A_{2,Eco}\frac{MR_1}{Pr_1}(V_1 + P_1 + U_1) + R_1 + C_1 + P_2 + U_2 + W_2 \\ &= 0.27 \times \frac{0.70}{1.00}(500 + 800 + 0) + 200 + 7 + 150 = 605\ kg\ CO_2E \\ &= 1210\ kg\ CO_2E/tPr_2 \end{aligned}$$



(a) **(b)**

Figure 6.16 Example of Economic Allocation – Co-Product Case – Allocated Product System
a) Virgin Product P_1, b) Recycled Product P_2

6.3.3.4 *Discussion of the Economic Allocation Methods*

Economic allocation methods have not been used extensively in published pulp and paper case studies (NCASI 2009, 2011).

The use of economic allocation is somewhat controversial. It is often justified based on the fact that the product's market value reflects the underlying economic reasons for its production, and that those economic reasons are important in determining how co-products are used (Jolliet, Saadâe, and Crettaz 2005). In other words, economic allocation is justified by the fact that the environmental load of a process is a consequence of the value this process generates for society (Huppes 1992). However, economic allocation provides results that vary over time due to fluctuations in market value of the various products, which can have significant effects on LCA results (Guinée, Heijungs, and Huppes 2004; Scientific Applications International Corporation 2006; Vigon et al. 1993).

There are some challenges specific to the application of economic allocation to the co-product case (pseudo-recycling). First, it requires that the full material life cycle be evaluated, and thus the economic values of all products in the life cycle must be known. Second, it assumes that all processes in the virgin product system, except for disposal, are shared between the virgin product and the subsequent recycled product. There is agreement in the literature, including the ISO 14044 Standard, that only the processes related to the production and processing of the virgin raw material should be considered shared between the various product systems[10] (Baumann and Tillman 2004; Ekvall and Tillman 1997; ISO 2006b). Although there is no consensus regarding what should be considered to be virgin raw material (i.e., is it

[10] The ISO 14044 Standard (ISO 2006b, p. 15) specifies that *"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."*

virgin pulp or wood chips?), this certainly does not include the use phase (and other conversion processes that may occur before the product is used). In several cases in the literature, only the production of the raw material is considered to be shared (Baumann and Tillman 2004, Ekvall and Tillman 1997), which would therefore exclude paper production.

6.3.4 *Other Relationship: Number of Uses (NOU) Method*

It has been proposed, in cases where the purpose of an LCA study is to study the environmental load of one specific product within a material life cycle, that the environmental load associated with virgin production and the effects of recycling should be distributed among the various products manufactured from the material based on physical properties such as mass (Curran 1996; Tillman et al. 1994). The ISO 14044 Standard and accompanying ISO 14049 Technical Report (ISO 2006b, 2012b) propose allocating the environmental load of virgin material production based on the percentage of fiber going to recycling, weighted by the inverse of the number of uses (u) of the fiber (Werner 2005). The environmental load of the portion of the fiber not recycled is allocated to the product system investigated. Werner (2005) argues that this is a form of system expansion. However, in doing so, allocation is not avoided.

Calculating the number of uses may not be straightforward. For this reason, a simplified procedure using a flow model based on mass flows and yield of the recycling processes is presented in the ISO 14049 Technical Report (ISO 2012b). This procedure is summarized and illustrated in Appendix A.

The allocation factor for virgin production is calculated as follows:

$$A_{i,NofU} = \begin{cases} 1 - \dfrac{E}{Pr_1} + \dfrac{E}{u \times Pr_1}, & i = 1 \\ \left(MR_1 - \dfrac{MR_1}{u \times Pr_1}\right)\left(\dfrac{1}{u-1}\right)\left(\dfrac{Pr_i}{\sum_{j=i}^{n} Pr_i}\right), & 2 \geq 0 \end{cases}$$

where MR_i is the quantity of used product i for recovery and Pr_i the quantity of product i.

It is generally assumed in the literature that the load from the virgin material production process (i.e., V_1) is shared between the uses of the material. Given that, the environmental load of the various products is calculated as follows (**Note:** the equation is valid only for cases where V_2, V_3, …, and $V_n = 0$):

$$E_{i,NofU} = C_{i-1} + R_{i-1} + A_{i,NofU}V_1 + P_i + U_i + W_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, and R_i the environmental load of recovered fiber processing.

However, in the paperboard example that is presented in the ISO 14049 Technical Report (ISO 2012b) both the virgin material production (i.e., virgin pulp) and the product (i.e., paper made from virgin pulp) manufacturing loads are assumed to be shared. Given that, the environmental load of the various products is calculated as follows:

$$E_{i,ISO14049} = \begin{cases} C_{i-1} + R_{i-1} + A_{i,NofU}(V_1 + P_1) + U_i + W_i, & i = 1 \\ C_{i-1} + R_{i-1} + A_{i,NofU}(V_1 + P_1) + P_i + U_i + W_i, & 2 \leq i \leq n \end{cases}$$

Note: These equations are valid only for cases where V_2, V_3, …, and $V_n = 0$). In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system to which equations for recycled products (i>1) are applied.

6.3.4.1 *Example*

This section presents example allocation calculations for the number of uses method using the two different sets of assumptions regarding shared loads discussed above. Figure 6.14, which is based on Figure 4.1, serves as the basis for the example calculations. The number of uses, u, is calculated for this example[11] as follows:

$$u = \frac{Pr_1 + Pr_2 + \sum_{i=3}^{n} Pr_i}{Pr_1} = 1.00 + 0.50 + 0.50 = 2.00\ t/t$$

The allocation factors are calculated as follows:

$$A_{1,NofU} = 1 - \frac{0.70}{1.00} + \frac{0.70}{2.00 \times 1.00} = 0.65$$

$$A_{2,NofU} = \left(0.70 - \frac{0.70}{2.00 \times 1.00}\right)\left(\frac{1}{2.00 - 1.00}\right)\left(\frac{0.5}{0.5 + 0.5}\right) = 0.175$$

The remaining 17.5% (1 – 0.65 – 0.175) allocation factor is applied to products 3 to n.

Assuming only the virgin material production process is shared, the environmental loads are calculated as follows:

$$E_{1,NofU} = C_0 + R_0 + A_{1,NofU}V_1 + P_1 + U_1 + W_1 = 0 + 0 + 0.65 \times 500 + 800 + 0 + 300$$
$$= 1425\ kg\ CO_2E = 1425\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,NofU} = C_1 + R_1 + A_{2,NofU}V_1 + P_2 + U_2 + W_2 = 7 + 200 + 0.175 \times 500 + 400 + 0 + 150$$
$$= 845\ kg\ CO_2E = 1689\ kg\ CO_2E/t\ Pr_2$$

Assuming that both the virgin material production and product manufacturing processes are shared (ISO 14049 example), the environmental loads are calculated as follows:

$$E_{1,ISO14049} = C_0 + R_0 + A_{1,NofU}(V_1 + P_1) + U_1 + W_1 = 0 + 0 + 0.65 \times (500 + 800) + 0 + 300$$
$$= 1145\ kg\ CO_2E = 1145\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,ISO14049} = C_1 + R_1 + A_2(V_1 + P_1) + P_2 + U_2 + W_2$$
$$= 7 + 200 + 0.175 \times (500 + 800) + 400 + 0 + 150 = 985\ kg\ CO_2E$$
$$= 1969\ kg\ CO_2E/t\ Pr_2$$

[11] The equation presented is appropriate for the example, but it is not applicable to all situations. See Appendix A.

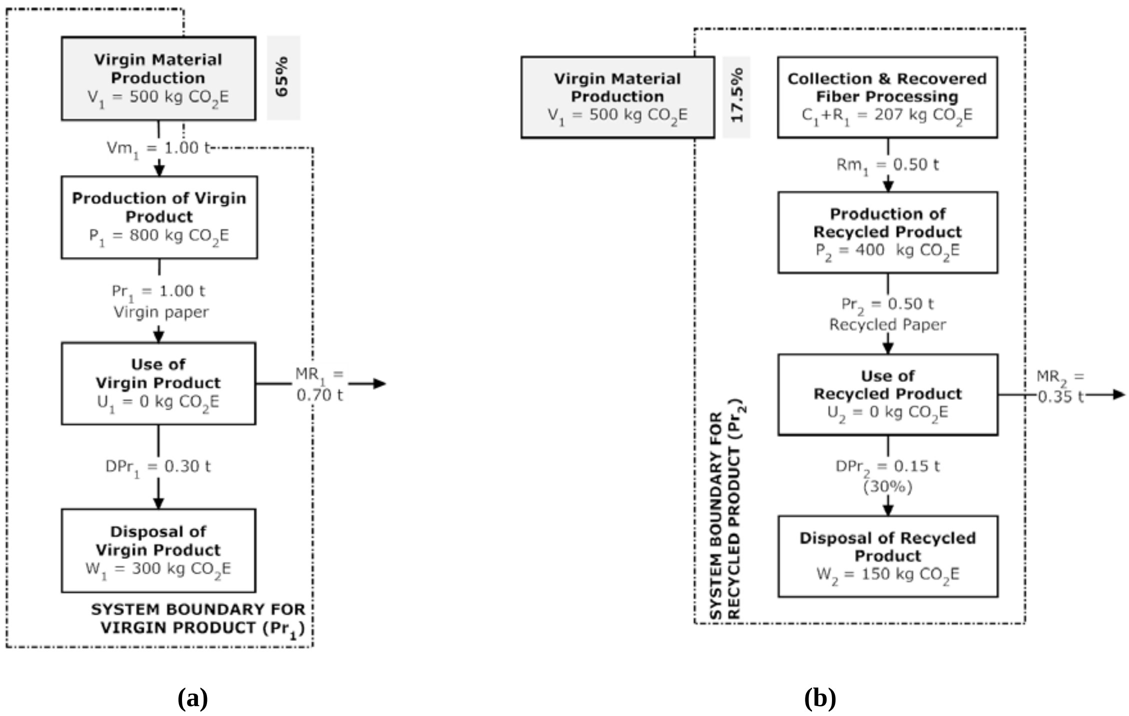


Figure 6.17 Example of Allocation Using the NOU Method
a) Virgin Product Pr_1, b) Recycled Product Pr_2

6.3.4.2 *Discussion of the Method*

The number of uses method was originally recommended by the American Forest & Paper Association (American Forest & Paper Association 1996) and has been used in several pulp and paper case studies (Environmental Resources Management 2007; Galeano, Smorch, and Richardson 2011; NCASI 2009, 2011). This method requires information that allows calculation of the number of uses. This is less information than is required for system expansion or allocation based on mass (Section 6.3.2). Indeed, it is not necessary to know or estimate the environmental load of all unit processes in the material life cycle. The procedure to calculate the number of uses provided in ISO 14049 (ISO 2012b) and summarized in Appendix A of this report, accounts for quality losses to a certain extent but in order for this procedure to be applied in practice, it is necessary to assume that everything that is recovered and used in non-tissue products is recycled infinitely (Guinée et al. 2002). This overestimates the number of uses. The method does not account for market reactions to changes in inflows and outflows of recovered material from the studied product system (Ekvall and Finnveden 2001). The method, as illustrated in the ISO 14049 Technical Report (ISO 2012b), does not mention how to allocate recycling processes, which suggests that these processes should be fully allocated to the products using the recovered material. The implicit assumption is that these processes are necessary to render the material high enough in quality to allow manufacture of the product. Finally, as with the substitution methods, the number of uses method can be seen as a risk-tolerant method because the accounting of some of the environmental load is postponed into the future (Frischknecht 2010).

6.3.5 *Allocation Methods Not Discussed in ISO 14044 or ISO 14049*

In the following sections, allocation methods that have been used in, or proposed for, the pulp and paper industry but that are not mentioned in the ISO LCA standards and technical reports (ISO 2006b, 2012b) are discussed. Note that ISO 14044 specifies that the three partitioning methods mentioned above (physical properties, economic value or number of uses) should be used if feasible. This was interpreted by Frischknecht (2010) as implying that the standard is not stringent regarding which basis for allocation to apply.

6.3.5.1 *Cut-Off Method*

The cut-off method, sometimes called the recycled content method, consists of separating (i.e., "cutting off") the material life cycle into the various product systems by applying an arbitrary definitive separation between them. In the literature, it is generally recommended that the separation be made just before the recycling processes (Curran 1996; Ekvall and Tillman 1997; Frischknecht 2010; Tillman et al. 1994; Werner 2005). This way the recycling process becomes the "raw material extraction and production process" for the recycled products. In other words, the cut-off method solves the recycling allocation situations on a process level by the setting of the system boundaries. Ekvall and Tillman (1997) proposed a refinement in which the recovery process would be partly allocated upstream using a co-product allocation method.

In this method, the basis for allocation of the virgin material production is the amount of virgin material used, the basis for allocation of the waste management processes is the loss of material from the technosphere to the environment, and the basis for allocation of the recycling processes is the use of recovered material.

One rationale for using this method is that through recycling, the system providing the recovered material benefits from having to do less waste management while the system using the recovered material benefits from not having had to produce the virgin material (Frischknecht 1994).

More specifically, in the example presented in Figure 6.1, the cut-off method is applied by allocating

- virgin material production process (V_1) to the virgin product (P_1);
- recycling process (R_1) to the recycled product (P_2); and
- waste management process to the product that is not recovered (W_1 to P_1 and W_2 to P_2).

Hence, the general equation for the cut-off method is

$$E_{i,CO} = R_{i-1} + V_i + P_i + U_i + W_i + C_i$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, and R_i the environmental load of recovered fiber processing.

6.3.5.1.1 *Example*

An illustration of application of the cut-off method is presented in Figure 6.18. The environmental loads attributable to the virgin and recycled products are calculated as follows:

$$E_{1,CO} = R_0 + V_1 + P_1 + U_1 + W_1 + C_1 = 0 + 500 + 800 + 0 + 300 + 7 = 1607\ kg\ CO_2E$$
$$= 1607\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,CO} = R_1 + V_2 + P_2 + U_2 + W_2 + C_2 = 250 + 0 + 400 + 0 + 150 + 3.5 = 754\ kg\ CO_2E$$
$$= 1507\ kg\ CO_2E/t\ Pr_2$$

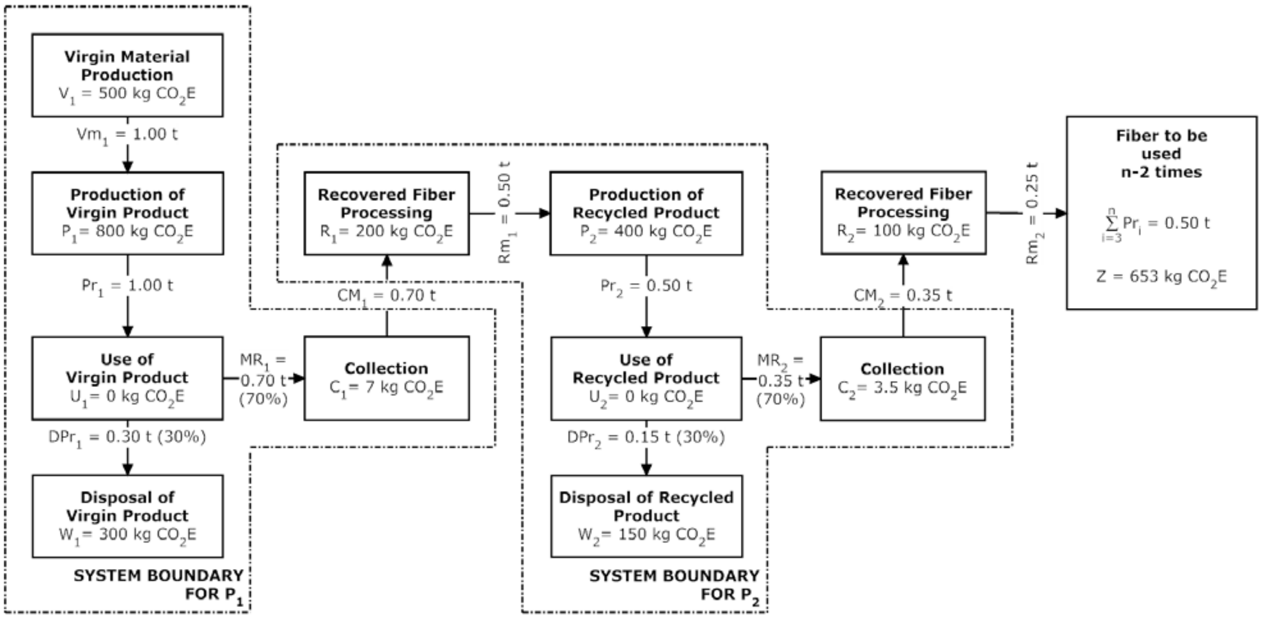


Figure 6.18 Example of Allocation Using the Cut-Off Method

6.3.5.1.2 *Discussion of the Method*

The cut-off method is the simplest method to apply (Baumann and Tillman 2004; Boguski, Hunt, and Franklin 1996; Ekvall and Tillman 1997; Werner 2005) and it has been used extensively for pulp and paper case studies (NCASI 2009, 2011).

As mentioned previously, Frischknecht (2010) compared the cut-off method with the end-of-life recycling method (described in Section 6.3.3.2) in terms of environmental sustainability and risk perception. He argues that the cut-off method is more aligned with the “strong sustainability concept,” defined by Neumayer (2003), where natural capital should not be substituted by man-made capital and thus environmental impacts are strictly linked to the product (man-made capital) that causes them, irrespective of any potential future reuse of it. Frischknecht also describes this method as a risk-averse method because emissions occurring today are allocated to today’s product and there is no load shifting to future generations.

It has been observed that the cut-off method ignores the relationships between the virgin and recycled products and that the recycled product would not exist if the virgin product was not manufactured first (Boguski, Hunt, and Franklin 1994; Curran 1996). According to Boguski, Hunt, and Franklin (1994) and to Werner (2005), it does not provide comprehensive information regarding the implications of recycling and gives no incentive for the preservation of the value of the material. The use of the cut-off method for studies of paper products has also been justified based on the ability of producers to control the level of recycled material they use and the lack of control they have on end-of-life recycling (Franklin Associates 2004).

It has also been suggested that the cut-off method may lead to suboptimal recommendations, as illustrated in the example presented in Figure 6.19 (Werner 2005). In this example, manufacturing of Product A requires 45 GJ of energy when produced from virgin material. The product is recycled with a recycling yield of 90%. Virgin material is used to compensate for the losses. The recycling process requires 5% of the energy required for producing the product from virgin material. Manufacture of Product B requires 20 GJ of energy when produced from virgin material. It is made from a material that is not recyclable, hence requiring the virgin material to produce each product life. The results show that Product A would appear to consume much more energy than Product B if the cut-off method is used (comparing the first life of Product A with the first life of Product B), because subsequent uses of the material are not considered. However, if a method that does consider the subsequent uses of the material is used, this would show that Product A becomes superior to Product B from an energy standpoint after three uses of the material. This suggests that the cut-off method may not be appropriate if the objective of the LCA is to select between two product options.

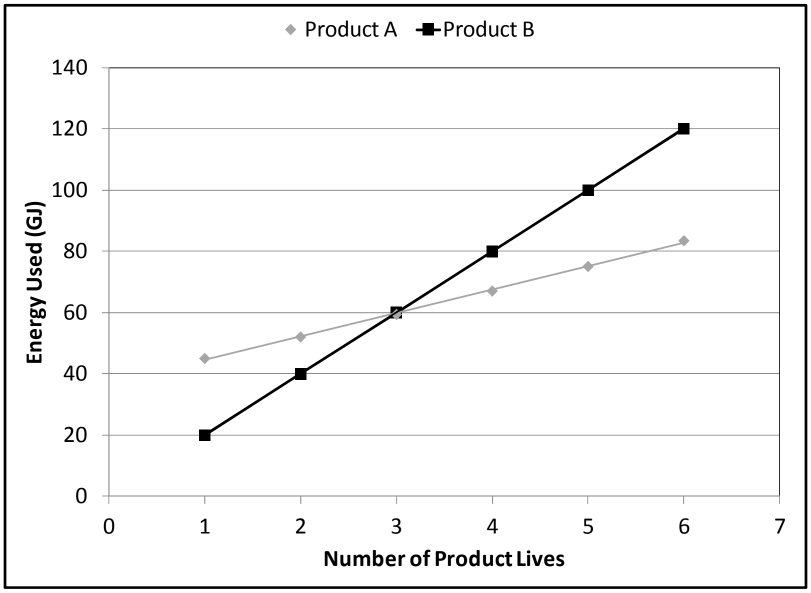


Figure 6.19 Cumulative Energy Used of Two Products Compared Over Several Product Lives [Fictitious data; example based after Werner (2005).]

6.3.5.2 *Extraction-Load Method*

The extraction-load method is based on the premise that, *"since all material will end up as waste, final waste management is an inevitable consequence of material extraction from the biosphere or geosphere"* (Ekvall and Tillman 1997). Hence, virgin material production and waste management processes are allocated to the product(s) using the virgin material (Fleisher 1994). Assuming that virgin material is produced only for the first product (i.e., $V_2 = V_3, \ldots, V_n = 0$), the general equation for the environmental load of the products calculated using the extraction-load method is

$$E_{i,EL} = \begin{cases} V_i + P_i + U_i + W_i + \sum_{j=i+1}^{n} W_j\,, & i = 1 \\ C_{i-1} + R_{i-1} + P_i + U_i, & 2 \le i \le n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, and R_i the environmental load of recovered fiber processing.

6.3.5.2.1 *Example*

An example application of the extraction-load method is presented in Figure 6.20. The environmental loads of the virgin and recycled product are calculated as follows:

$$E_{1,EL} = V_1 + P_1 + U_1 + W_1 + W_2 + \sum_{i=3}^{n} W_i = 500 + 800 + 0 + 300 + 150 + 150 = 1900\ kg\ CO_2E = $$
$$= 1900\ kg\ CO_2E/t\ Pr_1$$

$$E_{2,EL} = C_1 + R_1 + P_2 + U_2 = 7 + 200 + 400 + 0 = 607\ kg\ CO_2E = 1214\ kg\ CO_2E/t\ Pr_2$$

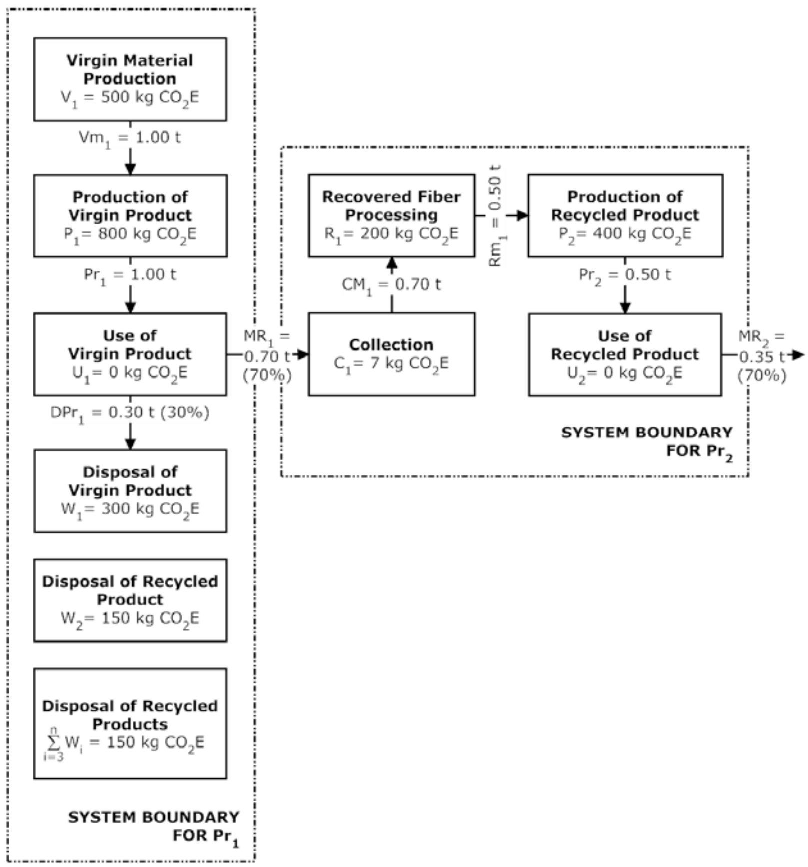


Figure 6.20 Example of Allocation Using the Extraction-Load Method

6.3.5.2.2 *Discussion of the Method*

This method has not been extensively used for pulp and paper case studies. A slightly modified version can be found in a study by the Paper Task Force (Environmental Defense Fund 2002).

This method is, in theory, easy to apply. However, to render the method accurate, the disposal of fiber losses that occur because of recycling should also be allocated to the virgin product, i.e.,

$$Wi\ allocated\ to\ virgin = Pr_i \times W$$

In addition, in this context, the environmental load of disposing of fiber losses should not be included in the environmental load of the recovery processes.

The method ignores the fact that the recycled product would not exist if the virgin product was not manufactured first.

6.3.5.3 *50/50 Method*

Note: This method is different from the 50/50 allocation approximation presented above.

This method allocates 50% of the environmental load of virgin material production and final waste management to the product using the virgin material, and the remaining 50% to any products not further recycled. The recycling processes are allocated 50% upstream and 50% downstream. The rationale for this method is that both supply and demand for recycled material are necessary to enable recycling (Ekvall and Tillman 1997).

The general equation for the environmental load of the products calculated using the 50/50 method is

$$E_{i,50/50} = \begin{cases} 0.50\left(1 + \frac{DPr_i}{\sum_{j=i}^{n} Pr_j}\right)\left(V_1 + \sum_{j=i}^{n} W_j\right) + P_i + U_i + 0.50(C_i + R_i), & i = 1 \\ 0.50\left(\frac{DPr_i}{\sum_{j=i-1}^{n} DPr_j}\right)\left(V_1 + \sum_{j=i-1}^{n} W_j\right) + 0.50(C_{i-1} + R_{i-1}) + P_i + U_i + 0.50(C_i + R_i), & 2 \le i \le n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and DPr_i the quantity of product i to disposal.

6.3.5.3.1 *Example*

When applied to the case study shown in Figure 5.1, the 50/50 allocation methods lead to the following environmental loads:

$$\begin{aligned} E_{1,50/50} &= 0.50\left(1 + \frac{DPr_1}{DPr_1 + DPr_2 + \sum_{j=3}^{n} DPr_j}\right)\left(V_1 + W_1 + W_2 + \sum_{j=3}^{n} W_j\right) + P_1 + U_1 \\ &\quad + 0.50(C_1 + R_1) \\ &= 0.50\left(1 + \frac{0.30}{0.30 + 0.15 + 0.15}\right)(500 + 300 + 150 + 150) + 800 + 0 \\ &\quad + 0.50(7 + 200) = 1728\ kg\ CO_2E = 1728\ kg\ CO_2E/t\ Pr_1 \end{aligned}$$

$$\begin{aligned} E_{2,50/50} &= 0.50\left(\frac{DPr_2}{DPr_1 + DPr_2 + \sum_{j=3}^{n} DPr_j}\right)\left(V_1 + W_1 + W_2 + \sum_{j=3}^{n} W_j\right) + 0.50(C_1 + R_1) + P_2 + U_2 \\ &\quad + 0.50(C_2 + R_2) \\ &= 0.50\left(\frac{0.15}{0.30 + 0.15 + 0.15}\right)(500 + 300 + 150 + 150) + 0.50(7 + 200) + 400 + 0 \\ &\quad + 0.50(3.5 + 100) = 693\ kg\ CO_2E = 1386\ kg\ CO_2E/t\ Pr_2 \end{aligned}$$

6.3.5.3.2 *Discussion of the Method*

This method has not been used significantly in recent LCAs of paper products (NCASI 2009, 2011). Although this method is applied at the material life cycle level, it requires less information than other methods at this level. It requires information on the recycling processes upstream and downstream, on virgin material production, and on final waste management. In theory, in order to determine how much final waste management occurs, it is necessary to know the number of uses of the material. However, this can be estimated by assuming

$$\sum_{i=1}^{n} DPr_i = Pr_1$$

In practice, some material losses occur during recycling, meaning that this equation would overestimate the environmental load of the whole material life cycle. For instance, in the example presented in Figure 5.1, the environmental load of the material life cycle would be overestimated by 12% using this equation. The method provides some information on the global implications of recycling because the entire material life cycle is considered.

6.3.5.4 *Others*

Other methods have been proposed; however, there are very few applications in the literature. These methods are briefly discussed below.

Methods based on quality losses have been proposed; however, no references to their use have been found in the literature. At least three of these methods can be found in the literature (Ekvall and Tillman 1997; Karlsson 1994; Wenzel, Hauschild, and Rasmussen 1996). These three methods, summarized by Ekvall and Tillman (1997), require that the difference in quality between the virgin product and the recycled product be known.

The first of these, originally proposed by Karlsson (1994), considers that man-made material is a valuable resource, that virgin material is required to obtain this resource, and that the recycling process is required because the quality of recovered material is too low to be reused without upgrading. Accordingly, the method allocates virgin material production based on the reduction in material quality, and allocates the recycling process to the upstream product system. Based on Ekvall and Tillman (1997), the following equations can be derived for this allocation method:

$$E_{i,Qa} = \begin{cases} \left(\dfrac{Q_i - Q_{i+1}}{Q_1}\right) V_1 + P_i + U_i + W_i + C_i + R_i, & 0 \le i \le n-1 \\ \left(\dfrac{Q_i}{Q_1}\right) V_1 + P_i + U_i + W_i, & i = n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and Q_i the material quality of Pr_i.

Note: This equation is valid only for cases where V_2, V_3, …, and $V_n = 0$). In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system for which equations for recycled products (i>1) are applied.

Ekvall and Tillman (1997) mention a second method based on quality losses, originally proposed by Wenzel, Hauschild, and Rasmussen (1996). This method also considers that man-made material is a valuable resource and that the recycling process is required because the quality of recovered material is too low to be reused without upgrading but considers that both the virgin material and final waste management are required to obtain this resource. Accordingly, the method allocates virgin material production and waste management based on the reduction in material quality, and allocates the recycling process to the upstream product system. Based on Ekvall and Tillman (1997), the following equation can be derived for this allocation method:

$$E_{i,Qb} = \begin{cases} \left(\frac{Q_i - Q_{i+1}}{Q_1}\right)\left(V_1 + \sum_{i=1}^{n} W_i\right) + P_i + U_i + C_i + R_i, & 0 \le i \le n-1 \\ \left(\frac{Q_i}{Q_1}\right)\left(V_1 + \sum_{i=1}^{n} W_i\right) + P_i + U_i, & i = n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and Q_i the material quality of Pr_i.

Note: This equation is valid only for cases where V_2, V_3, …, and $V_n = 0$). In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system for which equations for recycled products (i>1) are applied.

The third method based on quality losses, presented in Ekvall and Tillman (1997), considers that virgin material production, final waste management and the recycling process are all necessary to enable the combined function of the material. Accordingly, the method allocates virgin material production, final waste management and recycling based on the reduction in material quality, and the recycling process to the upstream product system. Based on Ekvall and Tillman (1997), the following equation can be derived for this allocation method:

$$E_{i,Qc} = \begin{cases} \left(\frac{Q_i - Q_{i+1}}{Q_1}\right)\left(V_1 + \sum_{i=1}^{n} (W_i + C_i + R_i)\right) + P_i + U_i, & 0 \le i \le n-1 \\ \left(\frac{Q_i}{Q_1}\right)\left(V_1 + \sum_{i=1}^{n} (W_i + C_i + R_i)\right) + P_i + U_i, & i = n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and Q_i the material quality of Pr_i.

Note: This equation is valid only for cases where V_2, V_3, …, and $V_n = 0$). In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system for which equations for recycled products (i>1) are applied.

In Section 6.3.5.2, the extraction-load method was presented. This method assumes that since all material will end up as a waste, waste management is an inevitable consequence of material extraction from the environment. Ekvall and Tillman (1997) also discussed a similarly constructed method but based on the opposite reasoning, known as the disposal-load method. This method assumes that to avoid reduction in the quantity of material available for man-made applications, material losses from the technosphere need to be replaced with virgin material. Accordingly, this method allocates virgin material production based on material disposal and allocates the recycling process upstream. This method was originally presented by other authors (Fleisher 1994; Klöpffer 1996; Östermark and Rydberg 1995). Based Ekvall and Tillman (1997), the following equation can be derived for this allocation method:

$$E_{i,DL} = \begin{cases} \left(\frac{W_i}{\sum_{i=1}^{n} W_i}\right) V_1 + P_i + U_i + C_i + R_i, & 0 \le i \le n-1 \\ \left(\frac{W_i}{\sum_{i=1}^{n} W_i}\right) V_1 + P_i + U_i, & i = n \end{cases}$$

where V_i is the environmental load of virgin material production, P_i the environmental load of the production of product i, U_i the environmental load of use of product i, W_i the environmental load of product i disposal, C_i the environmental load of collection of used product i, R_i the environmental load of recovered fiber processing, and Q_i the material quality of Pr_i.

Note: This equation is valid only for cases where V_2, V_3, …, and $V_n = 0$). In cases where a product system uses both virgin and recovered material, the product system must be split into a virgin product system to which equations for i = 1 are applied and into another product system for which equations for recycled products (i>1) are applied.

The disposal-load method promotes the development of recyclable products when the environmental load of recycling is lower than the combined load of virgin material production and waste management but gives no incentive for using recycled material.

The methods presented in this section are not further discussed in this document.

7.0 CASE STUDIES

In this section, case studies are presented that look at the following accounting-type questions and the effect of the choice of the allocation procedure.

- What are the main contributors to the life cycle environmental performance of a paper product?
- What are the environmental impacts attributable to a given paper product, and how does the environmental performance of a paper product vary from year to year?
- How does the environmental profile of a virgin paper product compare with the environmental profile of a recycled paper product?
- How does the environmental profile of a paper product that is used for a given function compare with the environmental profile of an alternative non-paper product that is used to fulfill the same function?

The example presented in Figure 5.1 will be used in each of these case studies. The nomenclature used for the various allocation methods used is presented in Table 7.1. It should be noted that these case studies are presented to illustrate the effect of using various allocation method in different contexts. The results obtained are specific to the example used and cannot be seen as absolute answers.

Table 7.1 Allocation Method Nomenclature

Nomenclature	Method	Nomenclature	Method
A**	Credit for end-of-life recycling	B	Credit for use of recovered material
C	Ekvall with 50/50 approximation	D*	Closed-loop
E*	Mass allocation	F*	Allocation using the economic value (intermediary case)
G*	Allocation using the economic value (co-product case, pseudo-recycling)	H	Modified number of uses (NOU)
I*	Number of uses (NOU, ISO 14049)	J	Cut-off
K	Extraction-load	L	50/50

*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.

7.1 Case Study #1: Determination of the Main Environmental Contributors

In this case study, the main contributors to the potential environmental impacts of the recycled paper product (example presented in Figure 5.1) for various allocation procedures are discussed. In other words, the question being asked is:

What are the main contributors to the life cycle environmental performance of a paper product?

To do so the following life cycle stages have been defined:

- production of raw material: upstream collection and processing of recovered fiber (if applicable), and any environmental load avoided or imported because of the use of recovered material;
- production: paper production; and
- end-of-life: downstream collection and processing of recovered fiber (if applicable), disposal, and any avoided or imported load due to the recovery for recycling.

The contributions of these three life cycle stages to the environmental performance of recycled paper are shown in Figure 7.1. The following observations can be made from this figure.

- Using the credit for use of recovered material (B) and Ekvall with 50/50 approximation (C) procedures for system expansion, the production of raw material gives a negative contribution (i.e., improves the environmental performance) meaning that it could be concluded that an opportunity for improvement is to increase the use of recovered fiber.
- The contribution of end-of-life varies from none to relatively significant.

This indicates that the choice of an allocation procedure may affect the identification of main contributors to the environmental performance of paper and the potential opportunities for improvement. It is thus important to understand the inherent value choices made when selecting an allocation method, as will be discussed later.

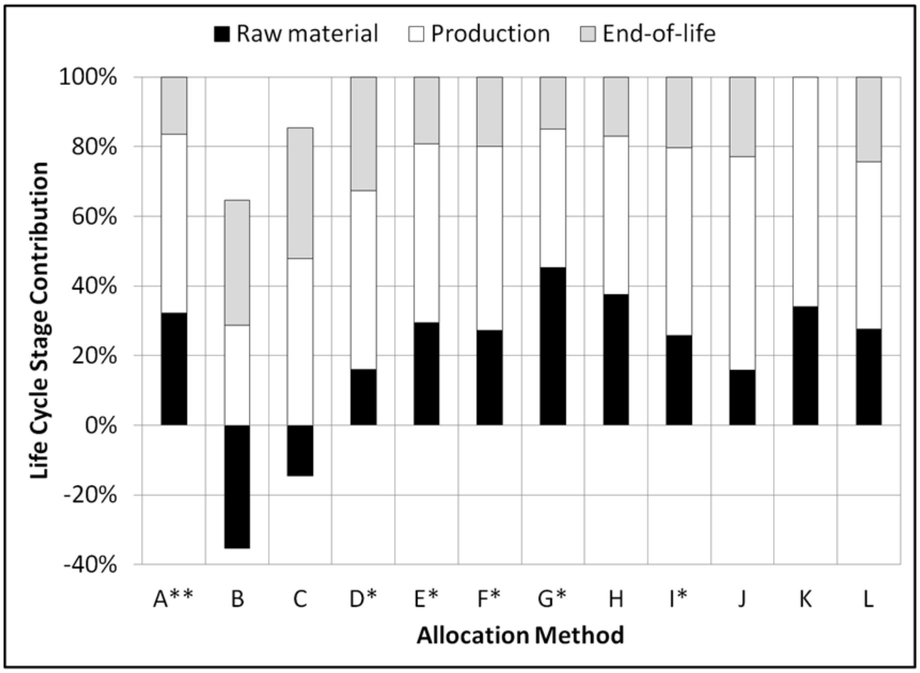


Figure 7.1 Estimated Contribution of the Life Cycle Stages to the Environmental Profile of Recycled Paper Given Various Allocation Methods
(*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.)

7.2 Case Study #2: Year-to-Year Evaluation of the Environmental Impact Attributable to a Given Paper Product

In this case study, the potential environmental load of the virgin product in Year 1 (as presented in the example illustrated in Figure 5.1) is compared with the potential environmental load of the same product in Year 2 under three different scenarios presented in Table 7.2. In other words, the questions being asked are:

What are the environmental impacts attributable to a given paper product?

How does the environmental performance of a paper product vary from year-to-year?

Table 7.2 Scenarios for Comparing the Allocation Methods for Year-to-Year Evaluations

Scenario	Description
Scenario I	The recovery rate (MR_1) is decreased from 70% to 50%.
Scenario II	The recovery rate (MR_1) is increased from 70% to 100%.
Scenario III	The environmental load of virgin production is decreased by 20% (i.e., V = 400 kg CO_2E/t).
Scenario IV	20% of the virgin production is substituted with recovered fiber (i.e., Vm_1 = 0.8 and Rm_0 = 0.2 t).

The results of the scenarios presented in Table 7.2 are depicted in Table 7.3. In this table a result larger than 1.0 indicates that the estimated environmental load observed in Year 2 is higher than the estimated load observed in Year 1 (environmental performance estimated to have decreased) and a result lower than 1.0 indicates that the estimated environmental load in Year 2 is lower than the estimated environmental load in Year 1 (environmental performance estimated to have improved).

This table shows that, for the example presented in this document, decreasing the recovery rate (Scenario I) is detrimental to the estimated environmental performance of the virgin product regardless of the allocation procedure used for recycling, with the exception of using a credit for end-of-life recycling (B). This is true only because the estimated environmental load of disposal is large enough to compensate for any gain that could be caused due to the applied allocation procedure. Some allocation procedures give lower estimated environmental load results when the recovery rate is reduced under certain conditions (e.g., low environmental load for disposal). The inverse is true when the recovery rate is increased (Scenario II).

Scenario III looks at improving the environmental performance of the virgin production process. This improves the total estimated environmental load regardless of the allocation procedure.

Finally, the results show that increasing the utilization of recovered fiber gives results that are dependent on the allocation procedure. This is because a decision is made on the treatment of recycled fiber as having a positive or negative effect on the environment.

Table 7.3 Impact of the Recycling Allocation Procedure for Evaluating Various Changes in the Life Cycle of a Paper Product

Allocation Method	**Scenario I**	**Scenario II**	**Scenario III**	**Scenario IV**
	Estimated Environmental Load in Year 2/Environmental Load in Year 1			
A	1.14	0.80	0.97	1.00
B	1.00	1.00	0.96	0.87
C	1.06	0.92	0.96	0.92
D	1.14	0.80	0.97	1.00
E	1.14	0.80	0.97	1.00
F	1.12	0.81	0.94	0.99
G	1.35	0.38	0.94	1.02
H	1.20	0.66	0.95	1.04
I	1.37	0.33	0.94	1.14
J	1.12	0.82	0.94	0.99
K	1.09	0.68	0.95	0.93
L	1.11	0.69	0.96	0.96
Minimum	1.00	0.33	0.94	0.87
Maximum	1.37	1.00	0.97	1.14
Average	1.15	0.72	0.95	0.99
Standard deviation	0.11	0.20	0.01	0.07

7.3 Case Study #3: Comparison of the Environmental Impacts Attributable to Virgin and Recycled Paper

In this section, the various allocation methods presented above are examined in the context of comparing virgin and recycled paper. In other words, the question being asked in this case study is:

How does the environmental profile of a virgin paper product compare with the environmental profile of a recycled paper product?

For this comparison, scenarios were defined and are presented in Table 7.4.

Table 7.4 Scenarios for Comparing the Allocation Methods

Scenario	Description
Scenario 0	This is the scenario described in the example presented in Figure 5.1, in which V > R (i.e., V = 500 kg CO_2E/t and R = 400 kg CO_2E/t) and the recovery rate is 70%.
Scenario 1	In this scenario, V < R (i.e., V = 400 kg CO_2E/t and R = 500 kg CO_2E/t) and the recovery rate is 70%.
Scenario 2	In this scenario, W is lower (i.e., W = 400 kg CO_2E/t) and the recovery rate is 70%.
Scenario 3	In this scenario, V > R (i.e., V = 500 kg CO_2E/t and R = 400 kg CO_2E/t) and the recovery rate is 30%.
Scenario 4	In this scenario, C+R > V+W (i.e., V = 200 kg CO_2E/t, W = 200 kg CO_2E/t and C+R = 600 kg CO_2E/t) and the recovery rate is 70%.

The various allocation methods are compared under Scenario 0 in Figure 7.2. The ratio of the estimated environmental load of the virgin product (E_1) to the estimated environmental load of the recycled product (E_2) is shown for the various allocation methodologies. A result lower than 1.0 (bold horizontal line) means that the virgin product has lower estimated environmental load than the recycled product, a result of 1.0 means that the loads are the same and a result greater than 1.0 means that the estimated environmental load of the recycled product is lower than that for the virgin product.

This figure shows that the estimated environmental load of the virgin product ranges from significantly lower to significantly higher than the recycled product depending on the allocation method used, even when considering only those methods specifically mentioned in ISO standards and guidance. The figure also shows that giving a waste management credit for using recovered fiber has the potential to yield results significantly different from other methods (especially if the estimated environmental load of disposal is high compared to other unit processes).

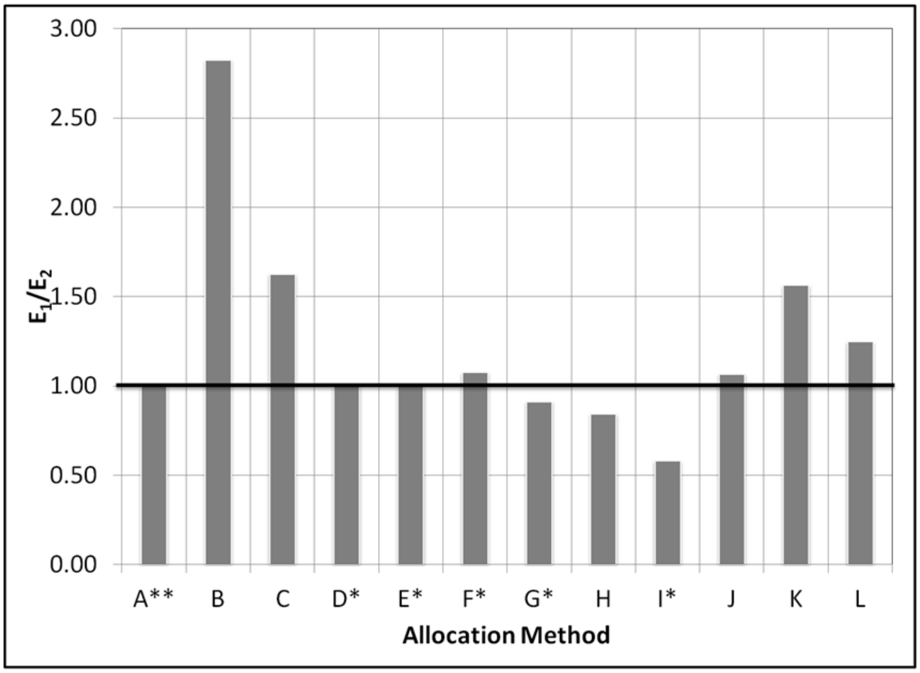


Figure 7.2 Comparison of Allocation Methods for Scenario 0
(*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.)

Figure 7.3 shows how the comparison of the virgin and recycled products is affected by the different scenario assumptions. Figure 7.4 shows how the estimated environmental performance of the virgin product (E_1) is affected by the various scenario assumptions while Figure 7.5 shows the same but for the recycled product (E_2). In the two latter figures, the values shown are ratios of estimated environmental loads obtained in Scenarios 1 through 4 to the estimated environmental load obtained in Scenario 0. A value lower than 1.0 (bold horizontal line) means that the estimated environmental load for a given scenario is lower than the estimated environmental load obtained in Scenario 0, a value of 1.0 means that the estimated environmental load for that scenario is the same as that for Scenario 0, and a value greater than one means that the estimated environmental load for the scenario is greater than that for Scenario 0.

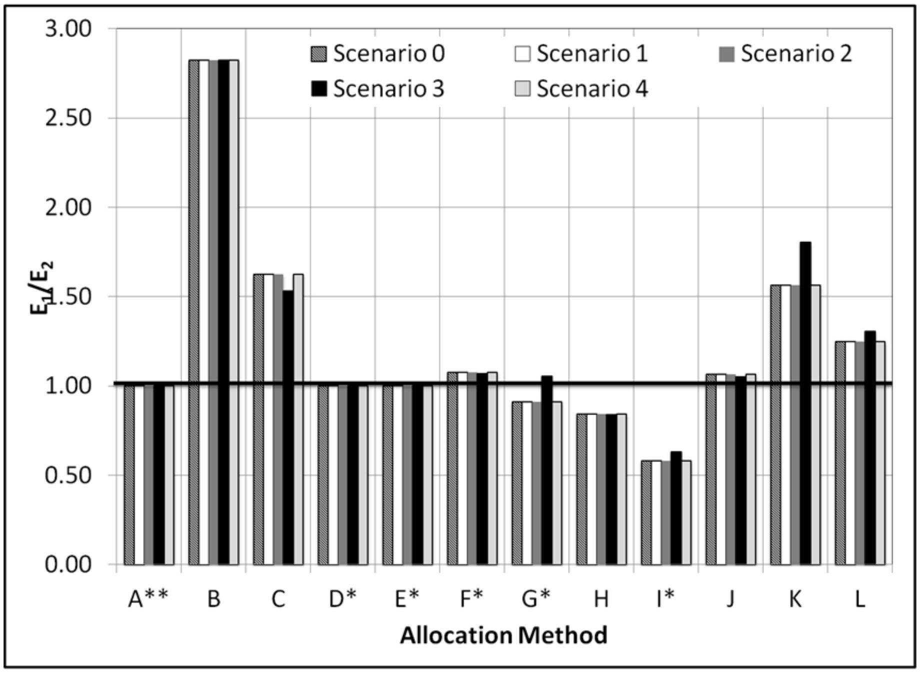


Figure 7.3 Effect of Various Allocation Methods and Scenarios on the Comparison of Virgin and Recycled Paper
(*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.)

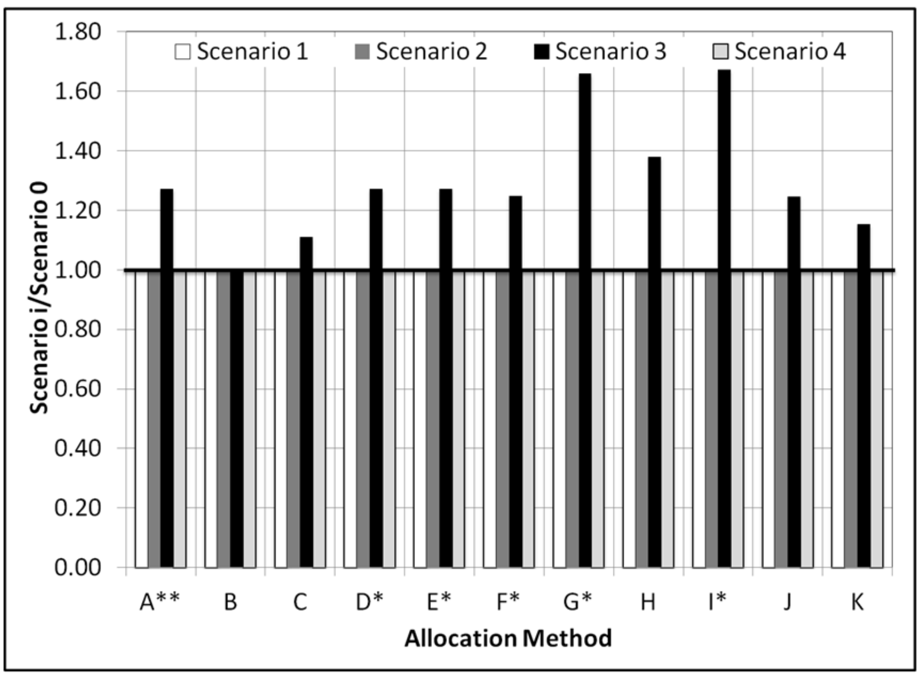


Figure 7.4 Effect of Various Allocation Methods and Scenarios on the Environmental Performance of the Virgin Product
(*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.)

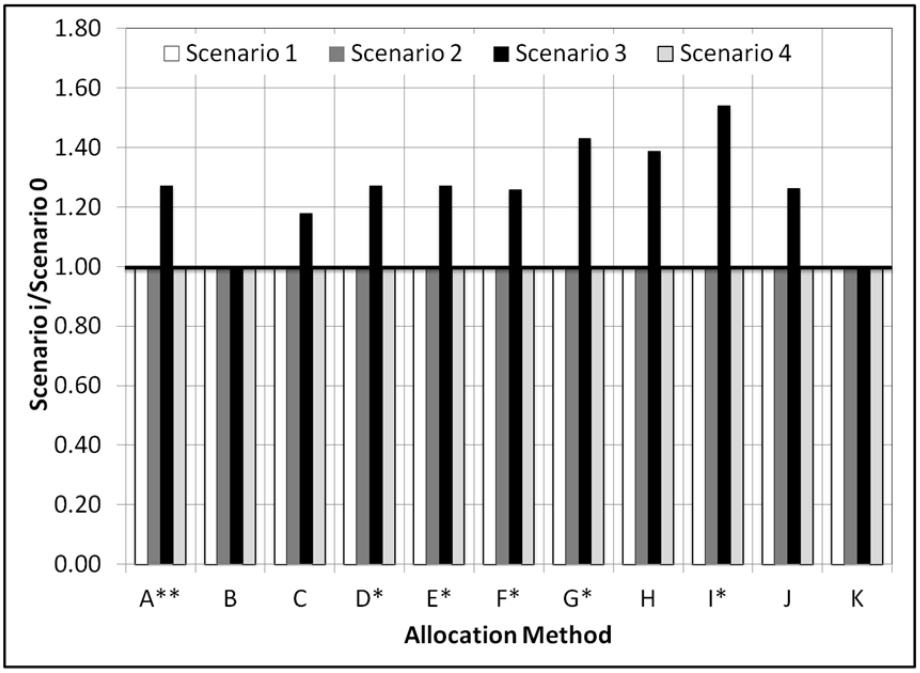


Figure 7.5 Effect of Various Allocation Methods and Scenarios on the Estimated Environmental Performance of the Recycled Product
(*Mentioned in ISO 14044 or ISO 14049. **Not specifically mentioned in ISO 14044 but a similar example provided in ISO 14049.)

The following observations can be made from the results presented Figures 7.3 through 7.5.

- The credit for end-of-life recycling (A), the closed-loop approximation (D), and mass allocation (E) attribute the same estimated environmental load to virgin and recycled products if they have the same end-of-life conditions.
- The comparison of virgin and recycled products is very sensitive to the estimated environmental load of virgin material production versus recovered fiber processing and to the recovery rate when applying economic allocation for pseudo-recycling (G), the number of uses method (I) as described in ISO 14049, and the extraction-load method (K).
- The individual estimated environmental performance of a given product is very sensitive to the choice of allocation method.
- For the system conditions studied in this report, using both the substitution method with the 50/50 approximation (C) and the number of uses method (I), two ISO-compliant methods, provides a reasonably good idea of the range of LCA results likely to be obtained under a variety of scenarios and allocation methods.

The results presented for Case Study #3 show that highly variable LCA results can be obtained depending on the allocation method applied and that this variability is, for the case study investigated, greater than the variability caused by changing the characteristics of the system itself. This indicates that there is no unambiguous outcome possible from LCA-based comparisons of virgin and recycled products.

The question asked in this case study was related to a comparison of the environmental attributes of virgin and recycled paper. One could have asked the question differently.

What is the environmental consequence of switching from virgin paper to recycled paper?

As discussed previously, the literature generally agrees that such a question requires that a system expansion approach be used, and thus the result is not affected by the choice of an allocation procedure. However, there are also some challenges associated with the system expansion methods as discussed previously.

7.4 Case Study #4: Comparison of the Environmental Impacts Attributable to Paper Product and a Non-Paper Alternative

In the example presented above (Scenario 0), the environmental load of the virgin product varies from 1,052 kg CO_2E/ton to 2,300 kg CO_2E, depending on the allocation procedure applied. In case study #4, it is assumed that 1 ton of virgin paper is used to produce 22,000 paper bags with a capacity of 6 gallons each. The functional unit (FU) is defined as "the domestic use of paper bags to contain 132,000 gallons of customer purchases and transport them." The question being asked is:

How does the environmental profile of a paper product that is used for a given function compare with the environmental profile of an alternative non-paper product that is used to fulfill the same function?

In order to compare those paper bags with plastic bags, it is necessary to determine the quantity X of plastic bags required to fulfill the same functional unit as with paper bags and to determine the estimated environmental load of producing these X bags. As illustrated in Figure 7.6, to be able to make a conclusion on the environmental superiority of one bag versus another, it is necessary for the environmental load of the X plastic bags to be outside the range of results obtained for the paper bags. This situation is further complicated because the same should be true for all impact indicators and the environmental load of the plastic bags will also represented in the LCA results by a range of results rather than as a single value.

The question asked above is related to a comparison of the environmental attributes of paper and plastic bags. One could have asked the question differently.

What is the environmental consequence of switching from paper to plastic bags?

The literature generally agrees that such a question requires that a system expansion approach be used, and thus the result is not affected by the choice of an allocation procedure. However, there are also some challenges associated with the system expansion methods as discussed previously.

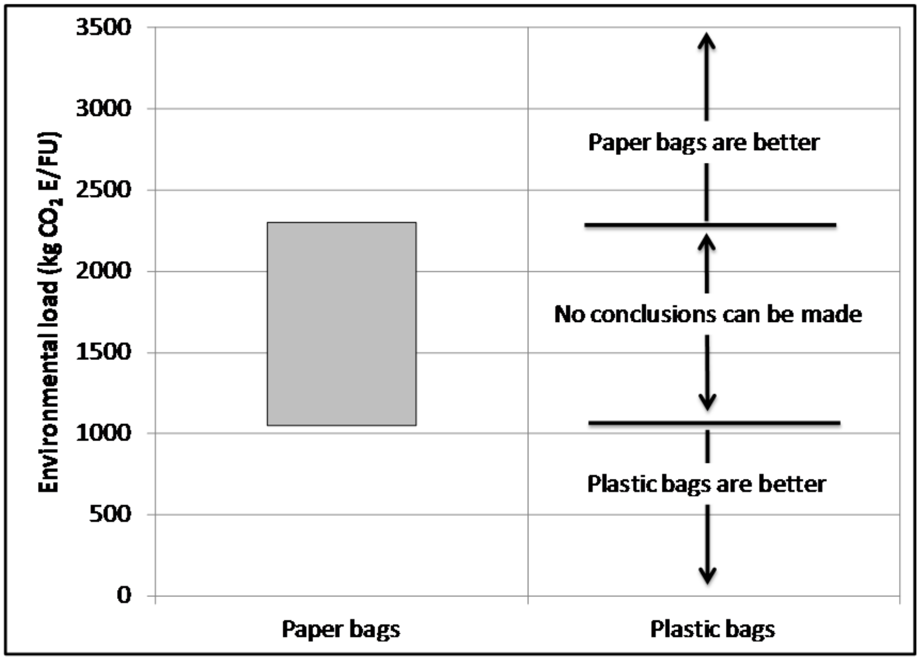


Figure 7.6 Comparing Paper and Plastic Bags Using Various Allocation Procedures for Recycling

8.0 CRITERIA FOR SELECTING AN ALLOCATION PROCEDURE FOR OPEN-LOOP RECYCLING

The International Organization for Standardization (ISO) has issued standards and guidance addressing many of issues related to recycling allocation, much of which have been summarized in this report. A body of literature and practice related to the ISO standards and guidance has emerged over time. Because companies may encounter this supplemental material, some of it was also reviewed. This supplemental material, however, lacks the international expert consensus and global standing attached to ISO standards and guidance, a limitation that companies should be mindful of.

It was shown in the previous section that the choice of an allocation method will have an effect on the LCA conclusions for most applications. This chapter summarizes first, the different allocation methods for recycling, and second, the various recommendations that can be found in the literature for selecting an appropriate allocation method.

This chapter does not limit any of the options available to companies under ISO standards and guidance. Companies are responsible for selecting and justifying the methods used for allocation in studies they perform and for any claims based on those studies.

8.1 *Summary of Allocation Methods*

Table 8.1 presents a systematic comparison of the different allocation methods for open-loop recycling that have been discussed in this document.

Table 8.1 Comparative Analysis of the Allocation Methods for Recycling

SL[12]	Allocation method	Description of method, its normative assumptions, set of values and behavior	Reference in ISO 14044	Advantages/limitations (Based on the literature)	Main references and use for pulp and paper case studies

C	Direct system enlargement (Section 6.2.3.1)	- Changes the objective of the study and the system boundary to include the co-products or their functions
		- Provides information on the global implication of recycling
		  - Stand-alone LCAs: provide a picture of the overall material life cycle
		  - Comparative LCAs: account for the market reactions to changes in inflows and outflows of recovered material from the studied product system
			System expansion	**Advantages:**
				• Only unambiguous solution to open-loop recycling allocation
				• More accurate model of the material life cycle
				Limitations:
				• Requires additional data and brings more uncertainty to the results because it necessitates several assumptions
				• Does not describe the individual environmental loads of the various products in the material life cycle
					Main reference:
					ISO (2006a)
					Pulp and paper applications:
					Some published case studies can be found

B	Substitution: Credit for end-of-life recycling (Section 6.2.3.2)	- End-of-life recycling substitutes for virgin material production - The difference between substituted virgin production and recycling is allocated to product system supplying the recovered material - Promotes recycling (where C+R <V)	None In ISO 14049: open-loop with closed-loop recycling procedure with expanded system	**Advantages:** • Quite easy to apply **Limitations:** • Requires additional data and increases uncertainty • Risk of violating the ISO mass balance requirement • Postpones the accounting of some load into the future[13] • Potential communication problems	**Main references:** Karlsson R. (1994), Fleischer (1994), Klöpffer (1996) **Pulp and paper applications:** Applied in many published pulp and paper case studies

[12] SL: system level, where A is for process-level, B is for product system level, and C is for material life cycle level (see Figure 5.1).
[13] Other methods may do this as well, but this method has been explicitly cited in the literature as doing so.

SL[12]	Allocation method	Description of method, its normative assumptions, set of values and behavior	Reference in ISO 14044	Advantages/limitations (Based on the literature)	Main references and use for pulp and paper case studies
B	Substitution: Credit for use of recovered material (Section 6.2.3.3)	- Use of recovered material avoids waste management - The difference between substituted waste management and recycling is allocated to product system using the recovered material - Promotes the use of recovered material (where C+R < W)	Not direct, described in the literature as subsumed in system expansion	**Advantages:** • Quite easy to apply **Limitations:** • Requires additional data and increases uncertainty • Risk of violating the ISO mass balance requirement • Potential communication problems	**Main reference:** Ekvall (1996) **Pulp and paper applications:** No good examples found in the literature
C	Substitution: Ekvall, 50/50 approximation (Section 6.2.3.5)	• For recycling to occur, both demand for and supply of recovered material are required • Assumes that 50% of an outflow of recovered material from the life cycle studied replaces virgin material and that the remaining 50% replaces recycled material from other sources; also assumes that inflow of recovered material results in 50% increased collection and 50% reduced use of cascade material in other products • Accounts for the market reactions to changes in inflows and outflows of recovered material from the studied product system	Not direct, described in the literature as subsumed in system expansion	**Advantages:** • Provides some limited insight on the global implications of recycling • Minimizes the maximum error that can result from the substitution method **Limitations:** • Requires additional data • Potential communication problems	**Main reference:** Ekvall and Weidema (2004) **Pulp and paper applications:** Was developed in the context of pulp and paper but very few published case studies can be found
B	Closed-loop procedure (Section 6.2.2)	• This method assumes that material recovered and the end-of-life of one product system is recycled into the same product system displacing the use of virgin material • Material is assumed to be reused indefinitely • Promotes end-of-life recycling for recycling (except where R + C > V + W)	Closed-loop procedure applied to open-loop recycling	**Advantages:** • Eliminates the need for allocation without requiring additional information **Limitations:** • Is applicable only under very specific circumstances • Is not additive	**Main references:** Lübkert et al. (1991), ISO (2012b) **Pulp and paper applications:** Applied in several published pulp and paper case studies

SL[12]	Allocation method	Description of method, its normative assumptions, set of values and behavior	Reference in ISO 14044	Advantages/limitations (Based on the literature)	Main references and use for pulp and paper case studies
C	Physical properties: mass (quasi-co-product) (Section 6.3.2)	• The material life cycle is treated as one unit process generating all the products and mass allocation is applied • Provides information on the global implications of recycling • Promotes recycling (supply and use of recovered material) where V+W > C+R	Physical properties (e.g., mass)	**Advantages:** • Acknowledges the inherent relationship between virgin and recovered material • Provides some information on the global implications of recycling **Limitations:** • Requires additional data and brings more uncertainty to the results because several assumptions are necessary	**Main references:** Boguski et al. (1994), Axel Springer Verlag AG et al. (1998) **Pulp and paper applications:** Some published case studies can be found
Economic value: general		The environmental load is allocated based on the economic value of the recovered material (see below for more information)	Economic value	**Advantages:** • Is applicable to all allocation situations **Limitations:** • Requires that the economic value of the recovered material be known at different points in the life cycle • Results fluctuate with market conditions	**Main references:** Huppes (1992), Guinée et al. (2002, 2004) **Pulp and paper applications:** No published case study found
A	Economic value: Intermediary case (Section 6.3.3.2)	• The environmental load of the process in which a change in economic value of the recovered material occurs (i.e., from negative or neutral to positive) is allocated based on the change in economic value • Recovered material is a waste until treatment is applied • What is being promoted depends on the economic values and of the environmental loads of the various processes		**Advantages:** • Is applicable to all allocation situations **Limitations:** • Requires that the economic value of the recovered material be known at different points in the life cycle • Results fluctuate with market conditions	

SL[12]	Allocation method	Description of method, its normative assumptions, set of values and behavior	Reference in ISO 14044	Advantages/limitations (Based on the literature)	Main references and use for pulp and paper case studies
C	Economic value: co-product case (pseudo-recycling) (Section 6.3.3.3)	• The recovered material is so valuable that it never has a negative value (i.e., it is a co-product rather than a waste). The environmental load of producing that product is allocated between the multiple usages • Recovered material is a valuable resource • Promotes end-of life recovery for recycling in all cases		**Advantages:** • Is applicable to all allocation situations • Acknowledges the inherent relationship between virgin and recovered material **Limitations:** • Requires that the economic value of the recovered material be known at different points in the life cycle • Results fluctuate with market conditions • Requires additional data and brings more uncertainty to the results because several assumptions are necessary	
C	Number of uses method (Section 6.3.4)	• Virgin material production (manufacturing of the virgin product (i.e., including paper production) as well if applied as in ISO 14049) is distributed to all product systems based on the number of uses of the recovered material • Recovered material is a valuable resource • Promotes end-of life recovery for recycling in all cases	Number of subsequent uses of the recycled material	**Advantages:** • Acknowledges the inherent relationship between virgin and recovered material • Provides some limited insight on the global implications of recycling **Limitations:** • Requires additional data and brings more uncertainty to the results because several assumptions are necessary	**Main reference:** ISO (2012b) **Pulp and paper applications:** Some published case studies can be found

SL[12]	Allocation method	Description of method, its normative assumptions, set of values and behavior	Reference in ISO 14044	Advantages/limitations (Based on the literature)	Main references and use for pulp and paper case studies
A	Cut-off method (Section 6.3.5.1)	• Each product system is attributed the environmental load directly caused by that system; the recovered material is considered to be a raw material for the downstream product system • Each product is only responsible for its direct environmental load • Promotes end-of-life recycling for recycling in all cases • Promotes use of recovered material where V>R	Not mentioned	**Advantages:** • Simple to apply • Does not postpone the accounting of environmental load in the future **Limitations:** • Does not acknowledge the inherent relationship between virgin and recovered material • Does not provide any information on the global implications of recycling	**Main references:** Frischknecht (1994) Ekvall and Tillman (1997) **Pulp and paper applications:** Applied in several published case studies
C	Extraction-load method (Section 6.3.5.2)	• Based on the premise that final waste management is an inevitable consequence of virgin material extraction • Promotes the use of recovered material if R < W	Not mentioned	**Advantages:** • Easy to apply if simplification made • Provides some information on the global implications of recycling **Limitations:** • Does not acknowledge the inherent relationship between virgin and recovered material	**Main reference:** Fleischer (1994), Ekvall and Tillman (1997) **Pulp and paper applications:** Very few published examples can be found
C	50/50 method (Section 6.3.5.3)	• Supply and demand are equally required for recovered material and both are necessary to enable recycling • Promotes the use of recovered material and end-of-life recycling for recycling where R < V+W	Not mentioned	**Advantages:** • Easy to apply if simplification made • Provides some information on the global implications of recycling **Limitations:** • Does not acknowledge the inherent relationship between virgin and recovered material	**Main reference:** Ekvall (1994), Ekvall and Tillman (1997), Strömberg et al. (1997) **Pulp and paper applications:** Very few published examples can be found

8.2 Criteria for Selecting an Allocation Procedure for Open-Loop Recycling

Selecting an appropriate allocation approach/method will always be somewhat subjective. However, guidelines are available in the ISO 14044 Standard, in the ISO 14049 Technical Report, and in the broader literature to limit subjectivity. For instance, it has been suggested in the literature that the allocation approach/method should be selected in a way that it

- conforms with the ISO 14044 requirements (Werner 2005);
- is consistent with the study objective (Baumann 1996; Baumann and Tillman 2004; Ekvall 1999b; Ekvall, Tillman, and Molander; Ekvall and Weidema 2004; European Commission 2010; Tillman 2000; Weidema 1998; Werner 2005);
- is consistent with the set of values that the study authors desire to convey and is transparent about it (Werner 2005);
- considers the characteristics of the material and of its market (Werner 2005);
- promotes resource efficiency (Werner 2005)[14]; and
- is acceptable to the intended audience and is feasible (Ekvall and Tillman 1997; Werner 2005).

Note that in some cases, certain of these criteria will be in conflict with each other, forcing the LCA practitioner to make some decisions as to which criteria are the most important. In addition, illustrating the variability of LCA results through the use of different allocation methods as part of a sensitivity analysis can improve transparency and develop perspective that is useful in the interpretation of the final results. A summary of the allocation methods in relation to the criteria mentioned above is presented in Figures 8.1 through 8.4. Each criterion is discussed further below.

[14] While Werner (2005) uses the promotion of resource efficiency as a criterion for selecting an allocation method, it can also be argued that promoting resource efficiency is only one of the sets of values that can be conveyed.

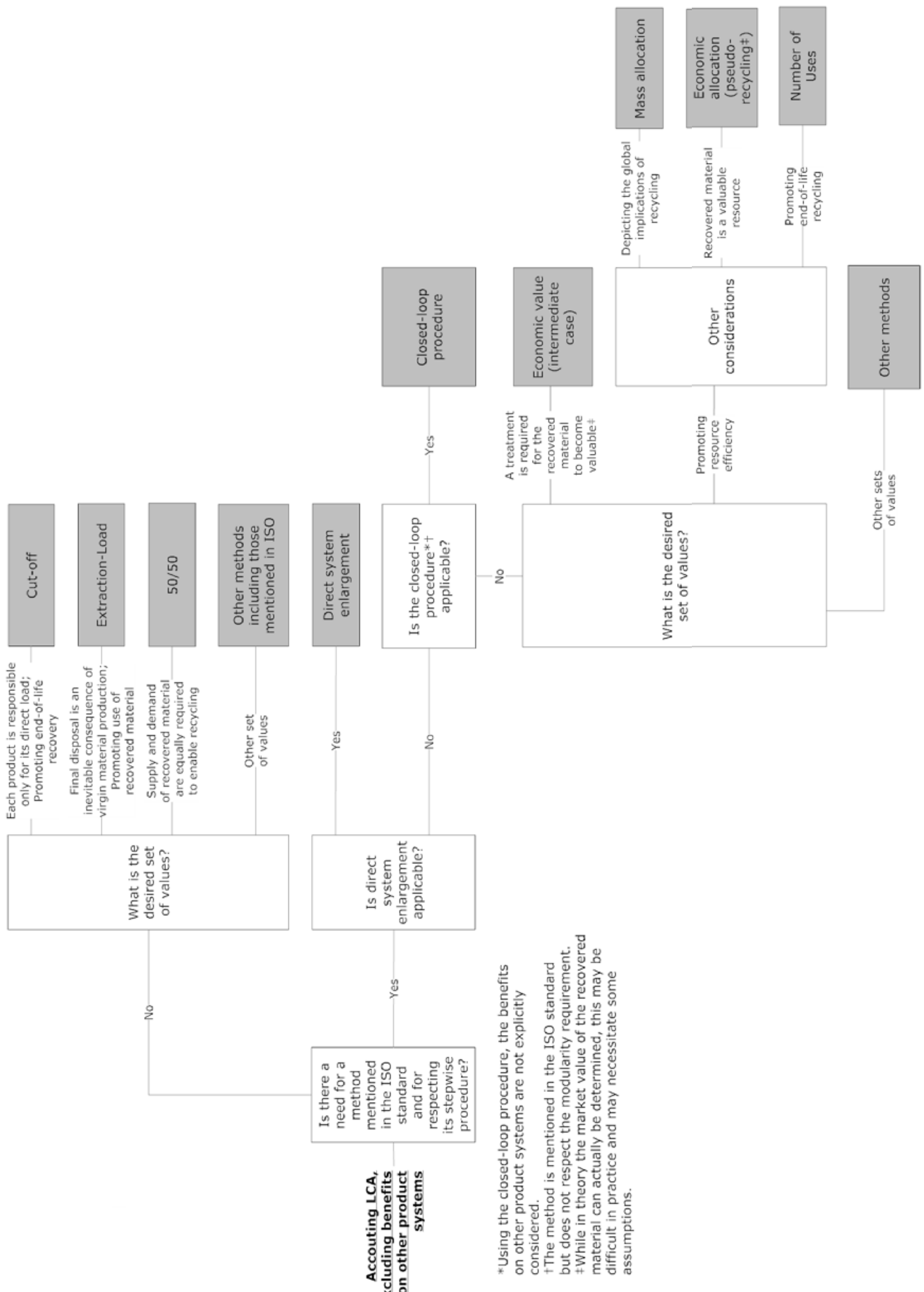


Figure 8.1 Summary of Allocation Methods That Can Be Used for Accounting LCAs That Exclude the Benefits on Other Product Systems

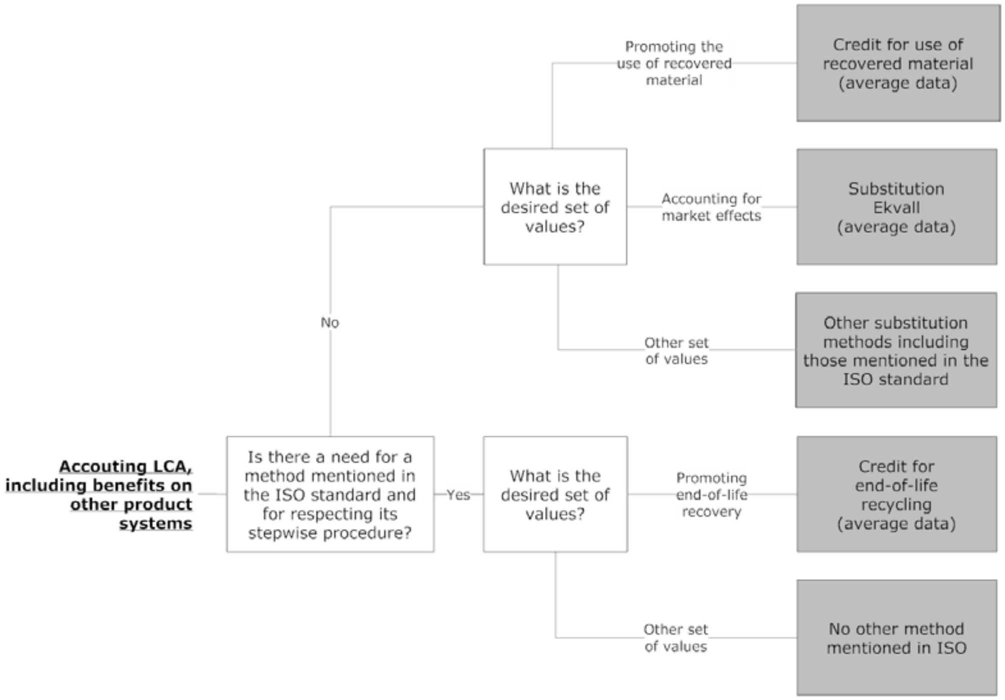


Figure 8.2 Summary of Allocation Methods that Can Be Used for Accounting LCAs That Include the Benefits on Other Product Systems
[Note: In this document, “Benefits” is interpreted in the broader sense of any interrelation with other product systems.]

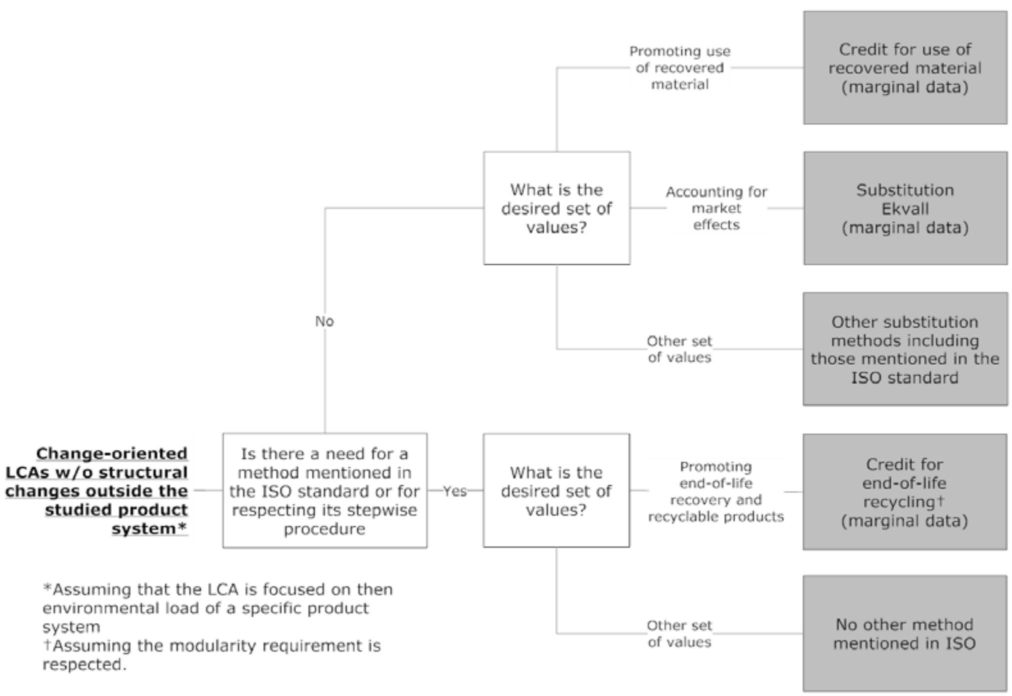


Figure 8.3 Summary of Allocation Methods that Can Be Used for Change-Oriented LCAs with No Structural Change outside the Product System Studied

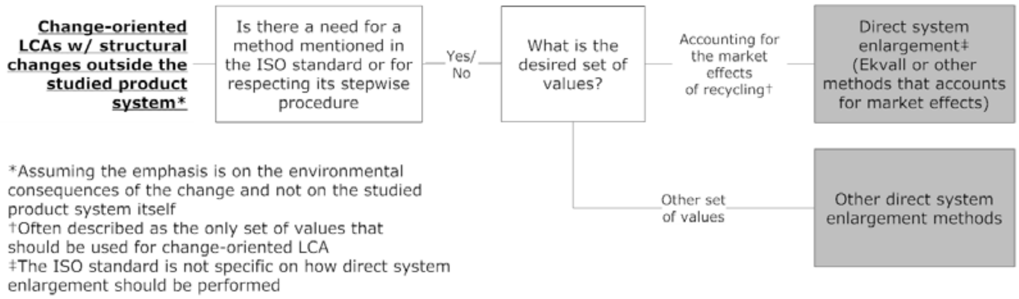


Figure 8.4 Summary of Allocation Methods that Can Be Used for Change-Oriented LCAs with Structural Changes outside the Product System Studied

8.2.1 *Conformity with the ISO 14044 Standard*

One criterion that can be used to select the allocation method for recycling is conformity with the ISO 14044 Standard (2006b). First, its general requirements should be considered, i.e., similar allocation methods *"shall"* be applied to inflows and outflows of recovered/recycled material, and mass and energy balances "*shall"* be preserved (ISO 2006b, p. 14) with the exception of the closed-loop procedure. On one hand, it has been argued that due to the inherent flexibility of the standard, no allocation method that fulfills the above requirements can be described as non-compliant with the ISO standard (Frischknecht 2010). However, the standard's use of language such as *"The allocation procedures for the shared unit processes […] should use, as the basis for allocation, if feasible […]"* may at a minimum indicate that the usage of a method not mentioned in the standard should be explicitly justified.

Note that the ISO 14044 Standard also requires that a sensitivity analysis be performed when more than one allocation method appears to be applicable.

Figures 81 through 8.4 above explicitly indicate which methods are mentioned in the ISO 14044 Standard or the ISO 14049 Technical Report.

8.2.2 *Consistency with the Study Objective*

As discussed previously in Section 4.2.2, although the ISO 14044 Standard does not provide any direction as to how the selection of an allocation method should reflect the study objective, there is general agreement in the literature that allocation should be avoided by subdividing the system whenever possible and that system expansion methods should be used for change-oriented LCAs.

Werner (2005) argues that, *a priori*, none of the system levels or allocation methods can be excluded, especially for accounting LCAs. Methods that consider the full material life cycle might be suitable for materials for which a relatively short material cascade can be unambiguously defined. This is true especially if LCA results can indirectly influence decisions related to material development. For materials with long life cycles (e.g., metals), allocation methods on the process or product system level may be more appropriate because methods at the material life cycle level would result in an indefinable quantity of product systems. Methods at the process or product levels are more simple and transparent.

Clearly, the study objective alone will generally be insufficient basis for selecting an allocation method.

Figures 8.1 through 8.4 above indicate the relationships between different study objectives and allocation methods.

8.2.3 *Set of Values to Convey*

The various implicit sets of values that can be seen to be reflected in the different allocation methods, as presented in Table 8.1, are

- to promote end-of-life recycling and the development of recyclable products (with or without conditions);
- to promote the use of recovered material;
- to promote both end-of-life recycling for recycling and the use of recovered material;
- to consider that the recovered material is a waste until a treatment is applied;
- to consider that the recovered material is a valuable material; and
- to account for market reactions to changes in inflows and outflows of recovered material from the studied product system.

These sets of values can be applied alone or in combination. Not only is transparency one of the guiding principles under the ISO 14044 LCA standard, it is also one of its requirements. Indeed, the standard requires *"full transparency in terms of value choices, rationales and expert judgements"* (ISO 2006b, p. 30). Clearly, the choice of an allocation procedure for open-loop recycling cannot be made without applying some value choices and, as demonstrated above and in the literature [see, for instance, Werner (2005)], this choice can have dramatic implications for the results. For this reason, selecting an allocation procedure that is consistent with the LCA user's set of values and explicitly explaining this choice in the LCA report is essential to maintaining transparency. Werner (2005) highlights that LCA users should be careful not to select an allocation method that contradicts the desired set of values.

8.2.4 *Characteristics of the Material and its Market and Resource Efficiency Considerations*

It has been argued in the literature (Atherton 2007; Dubreuil et al. 2010; Werner 2005) that the characteristics of the material and its market, as well as resource efficiency considerations, should be considered in the selection of a recycling allocation method for accounting LCAs. This was not depicted explicitly in Figure 8.1.

In this context, two commonly used allocation methods for recycling, the cut-off method (referred to by some authors as the recycled content approach) and the credit for end-of-life recycling method (referred to by some authors as the end-of-life recycling approach), are compared in the literature for the recycling of aluminum (Atherton 2007; Dubreuil et al. 2010; Werner 2005)[15].

In considering aluminum recycling, Atherton (2007), Dubreuil et al. (2010), and Werner (2005) noted that use of the cut-off method assumes that the use of recycled material is a good indicator of environmental benefit and thus that it is most useful for application to materials that would otherwise be burned or landfilled as waste. Dubreuil et al. (2010) also argue that this method *"aims to promote a market for recycled materials that is otherwise limited, uneconomic, or immature"* (Dubreuil et al. 2010, p. 623), which is not the case for the majority of metals, where the recycled metal market is fairly mature, and the economic basis for recycling metals continues to increase with rising energy costs and sensitivity to the risks associated with mining. Another challenge in using this method is that it may create market distortions and environmental inefficiencies in cases where there is a limited supply of recycled material (Atherton 2007; Dubreuil et al. 2010; Werner 2005). Indeed, if the supply of recycled material is not elastic, then usage of this material by one company may take it away from another company.

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[15] Werner (2005) also provides a wood product (railway sleepers) example. However, as the railway example does not consist of a cascade recycling allocation problem, the arguments made by Werner are less applicable to paper and hence, only the aluminum example is discussed here.

It is possible to translate this discussion to the paper industry. While the US and Canadian paper industries are committed to continually increasing their recovery rate (ICFPA 2011), for several types of recovered fiber (e.g., old corrugated containers and old newsprint), the recovery rates are approaching practical limits. This means that there is essentially a relatively stable pool of these types of recovered fiber, and if more is used in one type of product there will probably be less used in another type of product. For instance, it has been shown that forcing a maximum recovered fiber content in printing and writing papers in US and Canada would require that recovered printing and writing papers be shifted from newsprint, tissue and other grades to printing and writing grades, which would result in a net loss of total reusable fibers (Metafore 2006). Similar conclusions have been obtained for Scandinavian countries, where no evidence was found that forcing an increase in the recovered content of products normally made with chemical pulp would result in a significant environmental improvement (Byström and Lînnstedt 1997).

On the other hand, the credit for end-of-life recycling method is based on the premise that materials not recycled need to be replaced with primary materials and that by giving an incentive to making materials available after use, market efficiencies and environmentally preferable solutions will prevail and hence, market distortions and environmental inefficiencies will be avoided (Atherton 2007).

In addition, Werner (2005), Atherton (2007) and Dubreuil et al. (2010) underline the importance of considering changes in the material's inherent properties in the context of resource efficiency. In this context, Werner presents a modified credit for end-of-life recycling method (see Section 6.2.3.2), the value-corrected substitution (VCS) method, which accounts for losses in material quality and applies this method to the recycling of aluminum[16]. This is done by assuming only a partial substitution. In other words, the substituted processes (virgin material production) are multiplied by a correction factor to account for losses in quality. The challenge in taking this approach resides in defining this correction factor. Werner argues that for aluminum, no physical parameter can be found that reflects the loss in material quality over the entire material cascade and thus, only market prices can be used as a proxy for material devaluation over a product system. This is based on the assumption that the relative difference in price between virgin and recycled material reflects the differences in the material quality. A challenge related to this method is the variability of market prices over time. In cases where it would not be possible to assume that the market price of virgin and recycled material can be used as an indicator of the difference in quality of the material, another proxy would have to be defined. Werner also mentions that when applying the VCS method, special attention should be paid to the setting of system boundaries and more specifically to the attribution of the recycling processes to the right product systems. The credit for end-of-life recycling method, on which the VCS method is based, allocates the recycling process to the end-of-life and then credits the system with the avoided virgin material production. In order to apply this approach, it is necessary to distinguish between the specific virgin material production and recycling processes. Werner argues that to do this, it is necessary to identify the point in the production chain at which it is possible to identify equivalent virgin and recycled materials. For instance, "scrap" aluminum would not be considered equivalent to bauxite. Werner proposes that re-melted aluminum ingot is equivalent to virgin material ingot or in other words, the unit process that is equivalent to the processing stage of virgin aluminum is the re-melting of aluminum as ingot.

In theory, the method proposed by Werner (2005) is also applicable to the recycling of paper. It is often assumed in paper recycling LCAs that one ton of recycled pulp substitutes for one ton of virgin pulp (NCASI 2011). In practice, this may be what happens on the paper machine. However, it can be argued that because the number of uses of the fiber is limited, paper made from virgin fiber and paper made from recycled fiber do not have the same potential for future recycling and hence, assuming a one-to-one

[16] Werner argues that although in theory aluminum can be recycled infinitely, recycled aluminum may have different inherent properties (for instance higher zinc content), reducing its usability for some applications when compared to virgin aluminum.

substitution is not adequate for recycling allocation purposes. When applying the VCS method, a property (e.g., market price) must be determined to express this difference in quality of the virgin and recycled material. Finally, in order to apply this method, it is necessary to distinguish the specific virgin and recycled materials. Following Werner's rationale, while wood and recovered paper can hardly be considered to be equivalent materials, this is not the case for virgin and recycled pulps. Consequently, these two latter materials should be considered through applying the substitution method.

The VCS method is applicable for accounting LCAs in which it is an objective to make explicit the interrelationship between the studied product system and other product systems (See "accounting LCA including benefits on other product systems" in Figure 8.2). For accounting LCAs in which it is not the objective to explicitly express this interrelationship, other allocation methods that also promote end-of-life recycling have been proposed, for instance the number of uses method (see Section 6.3.4). Werner argues that the number of uses method is less suitable for metals that can be almost infinitely recycled, which would result in non-definable material life cycles. That said, the applicability of this method has been demonstrated for pulp and paper products (Environmental Resources Management 2007; Galeano et al. 2011; NCASI 2010). More specifically, it has been noted that recovered paper products have value because they retain useful properties of the original (virgin) product and effort has been expended to be able to produce them. Therefore, it has been suggested that some of the burden that was generated during the original production of these materials must be allocated away from the virgin production process and into the processed reclaimed material (Galeano et al. 2011). This has also been recommended for paper products by an international working group (American Forest & Paper Association 1996).

8.2.5 *Acceptability to the Intended Audience and Feasibility*

The relative acceptability to the intended audience and feasibility of various allocation methods are not highlighted in Figures 8.1 through 8.4 above.

It has been argued that recycling allocation methods should be as simple, manageable and transparent as possible (Werner 2005). Simplicity and feasibility of the methods has been discussed previously and a summary is provided in Table 8.1. It has also been recommended that the selected method be consistent with the attitude towards risk of the intended audience (Ekvall and Tillman 1997; Frischknecht 2010; Werner 2005).

9.0 CONCLUSIONS

In this report, the allocation methods for open-loop recycling that appear in the ISO 14044 Standard and guidance or which are frequently used in pulp and paper case studies in the literature are presented, illustrated, discussed, and compared. In considering these methods, it is important to bear in mind that the methods specifically mentioned in ISO standards and guidance enjoy a level of international expert consensus and global recognition that is not attached to those that have appeared only in the literature. This report does not limit any of the options available to companies under ISO standards and guidance. Companies are responsible for selecting and justifying the methods used for allocation in studies they perform and for any claims based on those studies.

It is shown that the choice of an allocation procedure for recycling can have a significant effect on the estimated environmental performance of individual products, even when the options are limited to those specifically discussed in the ISO standards and guidance. The choice of one allocation procedure over another generally has a significant effect on the results of an LCA for all types of applications. For internal types of applications (e.g., identification of main environmental contributors, tracking of year-to-year evaluation of environmental performance, etc.), it may be appropriate to employ more freedom when selecting an allocation procedure. That said, it is important to be transparent with regard to the selection made and also with regard to the set of values upon which the selection was based. Sensitivity analysis can be used to support internal applications of LCA. For comparative assertions, the ISO standard requires that sensitivity analyses be performed when several allocation methods appear to be applicable. In this context, experience has shown that, due in part to the sensitivity of the results to the selection of different allocation methods, LCA will seldom be useful for obtaining unambiguous conclusions if the objective is to compare virgin and recycled paper. Conclusions may be possible in some cases when the objective is to compare a paper product with an alternative.

Different criteria proposed in the literature for selecting an appropriate allocation method for recycling are also summarized in this report. These include conformity with the ISO 14044 Standard requirements, consistency with the study objective, consistency and transparency with the set of values that are being conveyed, the characteristics of the material and of its market and resource efficiency considerations, and the acceptability to the intended audience and feasibility.

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APPENDIX A

ISO/TR 14049:2012 NUMBER OF USES (NOU) METHOD

A.1 Introduction and Background

The ISO 14044 standard (ISO 2006) recommends, where allocation for open-loop recycling cannot be avoided through system expansion or by using a closed-loop approximation, that the basis of allocation procedures for the shared unit processes should be, in order (as feasible)

- 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 (see ISO/TR 14049)[17].

Note that the ISO 14044 standard also specifies that *"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"* (ISO 2012, p. 15).

The number of uses allocation (NOU) method as illustrated in the ISO 14049 technical report (ISO 2012) is based on physical properties and on the total number of uses of the material including the original "virgin" use and subsequent uses of the recovered material.

The ISO 14049 technical report (ISO 2012) illustrates the NOU method using a kraft bleached paperboard (KBPB) example. In this example, there are two systems receiving the recovered KBPB: tissue paper production and, for the remaining recovered KBPB, a series of other product systems practicing closed or open loop recycling. The NOU method is applied in order to calculate the fraction of the environmental load of virgin material production that will remain in the KBPB product system (virgin product) and which will thus be directly disposed of after use, and the fraction that will be exported to the totality of subsequent recycled products (note that the sum of all of these fractions should be equal to 1.0). The example does not attempt to estimate the fractions for the individual components, and treats the series of subsequent recycled product as one overall "totality" of recycled products. The reader is invited to directly refer to the ISO 14049 technical report for a complete description of this example.

In this appendix, the NOU method is illustrated for another product: office paper. The objectives of this office paper example are twofold:

1. to illustrate how to apply the NOU method in a case where there is a system of a series of different products receiving the recovered product (see Section A.2); and
2. to illustrate a suggested way on how to apply the method when undertaking an LCA on a recycled product (see Section A.3).

[17] In ISO 14044, the "number of subsequent uses of the recycled material" is described as a possible basis for allocation. In this report, this is referred to as the "number of uses" or "NOU" method as illustrated in ISO/TR 14049.

A.2 Virgin Office Paper Example

A.2.1 Recovery Rate and Distribution of Recovered Office Paper

According to U.S. Environmental Protection Agency (USEPA 2008), the average recovery rate of office paper in 2006 was 71.8% (i.e., $z_1 = 0.718$). According to AF&PA (American Forest & Paper Association 2007)[18], 19.8% of recovered office paper is used to make tissue paper, 62.8% is used to make paperboard, 10.4% is used to make printing and writing papers (P&W), 6.3% is used to make newsprint, and 0.7% is used to make packaging papers. This is illustrated in Figure A.1. In this figure, z_i is the recovery rate of product i, $u_{1,i}$ is the fraction of product 1 (virgin product) recovered in recycled product i (where $\sum u_{1,i} =1$, y_i is the yield of production of product j, product 1 is virgin office paper, product 2 is recycled tissue, product 3 is recycled paperboard, product 4 is recycled P&W papers, product 5 is newsprint, and product 6 is recycled packaging papers).

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[18] Assuming mixed papers can be considered representative for office paper.

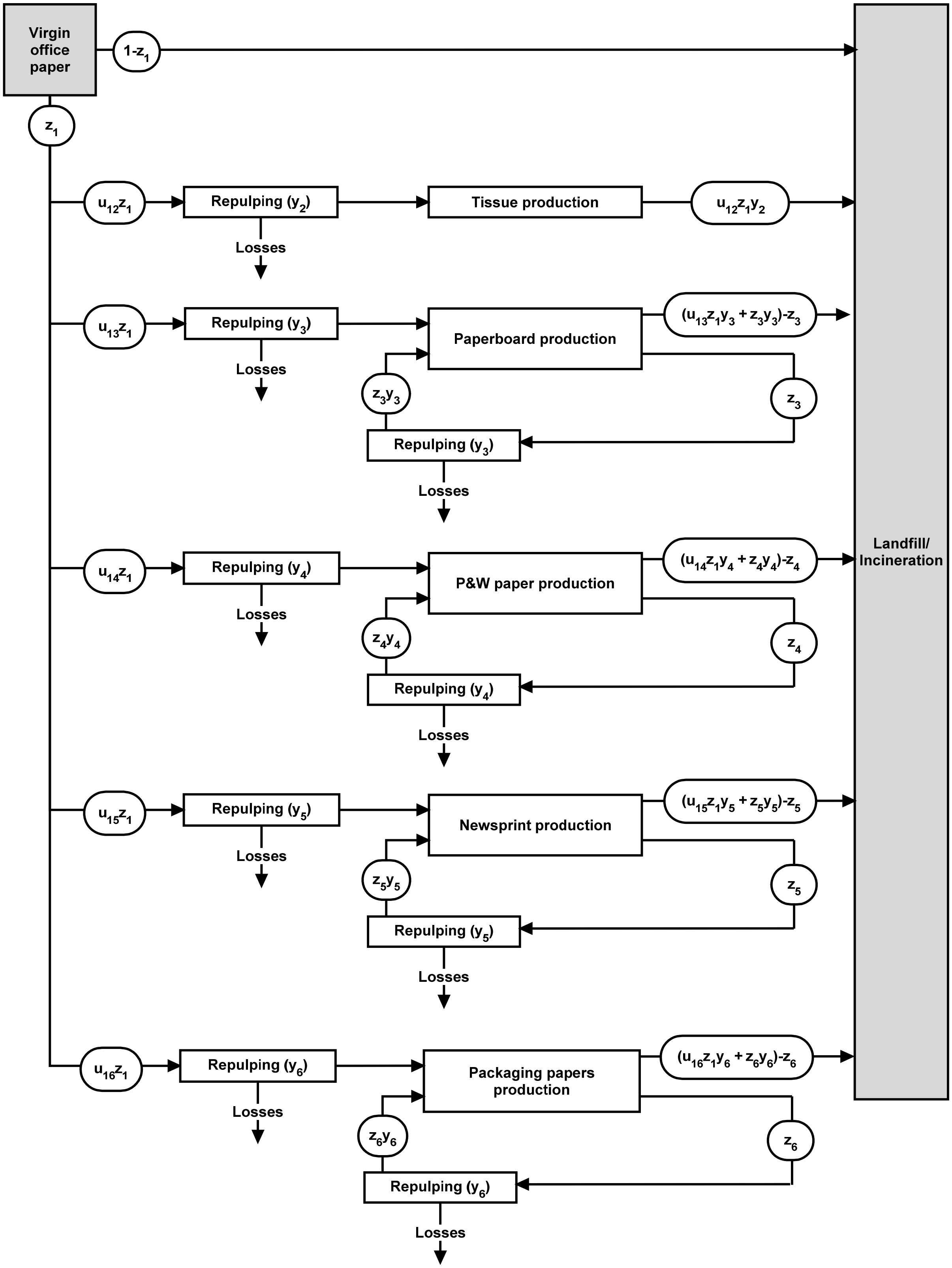

Figure A.1 Uses of Recovered Office Paper

Calculating the Number of Uses

For the recycling scenario presented in Figure A.1, the total number of uses (u) for recovered office paper (z_1) can be calculated with the data in Table A.1. The results are presented in Table A.2.

Table A.1 Data for Calculating the Number of Uses of Office Paper

z_1	0.718				
u_{12}	0.198	y_2	0.65		
u_{13}	0.628	y_3	0.90	z_3	0.635
u_{14}	0.104	y_4	0.65	z_4	0.500[c]
u_{15}	0.063	y_5	0.85[a]	z_5	0.753
u_{16}	0.007	y_6	0.90[b]	z_6	0.145[d]

[a] Average for newsprint. [b] Considered same as paperboard. [c] The average for P&W papers is lower than office paper only (0.718 compared with 0.500). [d] Average for packaging papers.
u_{ij} from (AF & PA 2007), z_i from (USEPA 2008) and y_i from (Clark, Hamilton, and Kleineau 1987)

To simplify the calculation procedure, the closed-loop assumption is made for the 2^{nd} and higher passes of recycling (i.e., $z_3 = x_3$, $z_4 = x_4$, $z_5 = x_5$, $z_6 = x_6$), as proposed in ISO 14049.

Table A.2 Number of Uses Calculation for Recovered Office Paper

u	=			1 use	First use of virgin product (office paper)
	+	$z_1u_{12}y_2$		0.09 uses	Tissue uses from recovered office paper
	+	$z_1(u_{13}y_3)(1/(1-z_3y_3)^*$		0.95 uses	The sum of recycled paperboard uses from recovered office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)
	+	$z_1(u_{14}y_4)(1/(1-z_4y_4)^*$		0.07 uses	The sum of recycled P&W paper uses from recovered office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)
	+	$z_1(u_{15}y_5)(1/(1-z_5y_5)^*$		0.11 uses	The sum of recycled newsprint uses from recovered office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)
	+	$z_1(u_{16}y_6)(1/(1-z_6y_6)^*$		0.01 uses	The sum of recycled packaging paper uses from recovered office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)
	=			**2.23 uses**	**Total number of uses**

*For more details on how these equations have been derived, please refer to the ISO/TR 14049 document.

A.2.3 Determining the Allocation Factor and Attributing the Final Loading to the Different Systems

The allocation factor for virgin production (A_1) can be calculated as follows:

$A_1 = (1- z_1) + (z_1/u) = (1- 0.718) + (0.718/2.23) = 0.60$

This means that 60% of the environmental load from producing virgin office paper is allocated to virgin office paper.

Likewise, the totality of the recycled product uses will receive an allocation factor (A_R) equal to

$A_R = z_1(u - 1)/u = 0.718(2.23 - 1)/2.23 = 0.40$

meaning that 40% of the virgin production load is allocated to the totality of recycled products made from recovered virgin office paper.

It is very important that the sum of allocation factors equal to 1.00, i.e.,

$A_1 + A_R = 0.60 + 0.40 = 1.00.$

The fraction of virgin production load allocated to the totality of recycled products made from the virgin product (A_R) can be further allocated between the different recycled products (tissue, paperboard, P&W, newsprint, and packaging papers) using recovered office paper. The ISO/TR 14049 technical report example considers that the tissue paper is discarded, and thus the example does not provide further calculations for this case.

A.3 Applying the NOU Method to an LCA of a Recycled Product

The discussion in this section goes beyond what is presented in ISO/TR 14049, which addresses the allocation of burdens for an initial virgin fiber product but does not get into the distribution for different components.

A.3.1 Distribution of the Fraction of the Virgin Production Load Allocated to the Totality of Recycled Products across the Different Recycled Products

The above explanation under A.2 shows how the NOU method can be applied within an LCA of a virgin product. In that example, the fraction of virgin production load that remains in the office paper system and the fraction of virgin production load that is exported to the totality of recycled products were identified and calculated based on the NOU method presented in ISO 14049:2012. Both the virgin office paper presented above and the KBPB example presented in ISO 14049:2012 are undertaken from the perspective of the virgin product. Hence, in these examples, it was not necessary to discuss how to distribute the fraction of the virgin production load allocated to the totality of recycled product uses (A_R) across the different known recycled products. To apply the NOU method on an individual recycled product one would need to distribute the recycled allocation factor (A_R) to each of the individual recycled products. This will be explored here by continuing to use the above example based on office paper.

For this example, we consider that the fraction of office paper recovered into each of the recycled products ($u_{1,i}$) is a suitable basis for this distribution[19]. This is illustrated in Table A.3.

[19] Another basis could have been selected, for instance the number of uses of recovered office paper into the individual recycled products (as illustrated in Table A.2).

Table A.3 Estimated Allocation of A_R to the Different Recycled Products Based on the Fraction of the Recovered Office Paper That Is Used in Each Recycled Product

Recycled product made from recovered office paper		Fraction of office paper recovered into recycled product ($u_{1,i}$)*	Final virgin production load of office paper allocated to recycled product
2	Tissue	0.198	A_2 = 0.198 x 0.40 = 0.08
3	Paperboard	0.628	A_3 = 0.628 x 0.40 = 0.25
4	P&W papers	0.104	A_4 = 0.104 x 0.40 = 0.04
5	Newsprint	0.063	A_5 = 0.063 x 0.40 = 0.03
6	Packaging papers	0.007	A_6 = 0.007 x 0.40 ≈ 0.00
Total		**1.00**	**0.40 = A_R**

*See Table A.1 for nomenclature.

It is very important that

$A_2 + A_3 + A_4 + A_5 + A_6 = A_R$.

The information derived to this point indicates the following:

- 60% of the virgin production load of office paper is allocated to office paper; and
- 40% of the virgin production load of office paper is allocated to the totality of the recycled products made of recovered office paper, and that it is split as follows: 8% to recycled tissue, 25% to recycled paperboard, 4% to recycled P&W papers, 3% to recycled newsprint, and 0% to recycled packaging papers.

All the information derived above was on the basis of 1 use of virgin office paper.

A.3.2 Application of the Number of Uses Method to a Recycled Product

If the objective of the LCA were to evaluate a product made of recovered office paper, the basis for the study would be more likely to be 1 use of recycled product. In this case it would be necessary to estimate how much virgin production load to allocate to 1 use of recycled product.

As an example, consider an LCA that is interested in "***1 use of recycled paperboard made from recovered office paper.***" (See Example B in Table A.4. Note that this is outside the scope of ISO14049:2012). In Table A.2 it was shown that, when considering industry average statistics, 1 use of virgin office paper generates 0.95 uses of recycled paperboard from recovered office paper. In Table A.3 it was estimated that the fraction of virgin production load of office paper allocated to the recycled paperboard product was 0.25. Hence, if the LCA study is interested in 1 use of recycled paperboard made from recovered office paper, the estimated fraction of virgin production load of office paper allocated to that 1 use of recycled paperboard product would be calculated as follows:

Estimated fraction of virgin production load of office paper allocated to 1 use of recycled paperboard = Final virgin production load of office paper allocated to recycled paperboard/ Uses of recovered office paper into recycled paperboard = 0.25/0.95 = 0.26

Table A.4 also shows the same approach for LCA studies that would be interested in other recycled products from recovered office paper (Example A, C, D, and E).

Table A.4 Estimated Allocation Factors per 1 Use of Each Recycled Product

Basis for the study: 1 use of virgin office paper that is recovered				**Basis for the study: 1 use of the individual recycled products that use recovered office paper**
Example no.	**Uses of recovered office paper into the different recycled products (based on Table A.2)**		**Estimated Fraction of virgin production load of office paper allocated to product (based on Table A.3)**	**Estimated Fraction of virgin production load of office paper allocated to 1 use of recycled product**
A	Tissue use from recovered office paper	0.09 uses	$A_2 = 0.08$	0.08/0.09 = 0.89
B	The sum of recycled paperboard uses from office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)	0.95 uses	$A_3 = 0.25$	0.25/0.95 = 0.26
C	The sum of recycled P&W paper uses from office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)	0.07 uses	$A_4 = 0.04$	0.04/0.07 = 0.57
D	The sum of recycled newsprint uses from office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)	0.11 uses	$A_5 = 0.03$	0.03/0.11 = 0.27
E	The sum of recycled packaging paper uses from office paper (i.e., first pass, second pass, third pass, ..., n^{th} pass)	0.01 uses	$A_6 \approx 0.00$	0.00/0.01 ≈ 0.00

*Note: $A_2 + A_3 + A_4 + A_5 + A_6 = A_R = 0.40$

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