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Life Cycle Assessment of fresh dairy packaging at ELOPAK

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Master in Industrial Ecology
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MASTER THESIS

for

Student
Vegard Ruttenborg

Fall 2016

Life cycle assessment of new beverage packaging designs at ELOPAK

Livsløpsanalyse av nye løsninger for drikkevareemballasje hos ELOPAK.

Background and objective

In 2015 the EU commission put forward a plan of action for a circular economy and a resource efficient development in Europe. The EU waste directive and Circular Economy package includes few, but concrete measures to stimulate Europe's transition towards a circular economy where the goal is to stimulate economic growth, increase global competitiveness and generate new jobs. These measures have a strong focus on downstream activities, however, companies often need to evaluate the whole life cycle when assessing alternative product solutions for packaging products. LCA allows such an analysis by taking into account all activities throughout the life cycle of a product.

LCA has become a common tool to analyse the environmental performance of packaging products. As a result, there is a growing literature within the field. A literature study was carried out as a project work leading into this MSc thesis. The study focused on examining and comparing different LCA studies on PET bottles and carton used for beverage packaging. By taking this experience one step further this MSc thesis will focus on the execution of the LCA methodology to evaluate the environmental performance of beverage packaging products by the company ELOPAK.

The objective of this MSc thesis is to conduct an LCA of a 1 litre standard carton for fresh/chilled milk and to find the alternative environmental footprint for utilizing renewable PE for coating and closures. The functional unit of the study is the packaging and distribution of 1 litre of chilled milk in a cradle-to-grave perspective. The carton reflects the European average for transport distances, waste management etc.

The work is carried out in contact with the company ELOPAK, with Kristian Hall as contact person. The study aligns product specifications with what are current priorities by the company, and relies to a large extent upon data provided by the company.

The following tasks are to be considered:

1. Carry out a literature study on life cycle assessment of products relevant to the objective of this work.
2. Provide a description of the products you are studying, and collect the data and information needed to perform LCA modelling of the given product systems.
3. Develop LCA models (preferably in Arda) according to state-of-the-art LCA methodology, including appropriate choices on goal and scope, system boundaries, as well as relevant data inputs and assumptions for the given functional unit of the analysis.
4. Report results and uncertainties (including a sensitivity analysis) of your study, including a contribution analysis.
5. Discuss the overall findings of the study, its agreement with literature, strengths and weaknesses of the methods, and its implications for practical implications and further research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 5th September 2016

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Preface

This thesis was submitted in 2017 as a requirement to conclude a degree of Master of Science in Industrial Ecology at the Norwegian University of Science and Technology (NTNU). The work was conducted in collaboration with Elopak which formulated the problem statement and provided information of the product under study.

The original problem statement of this study involved a comparison of two different milk carton products. Difficulties in the data collection process made it necessary to only include one of the products in this assessment. As a consequence, the title of this thesis is changed.

I want to thank Kristian Hall and Marianne Groven at Elopak for giving me the opportunity to conduct this masters thesis by assessing an Elopak product. They have been very helpful and cooperative throughout the process and provided me with valuable business experience for future challenges. I also want to thank my supervisor at NTNU, Helge Brattebø for setting me in contact with Elopak and for his expert guidance and support.

Vegard Ruttenborg
February 2017

Abstract

Nearly all food and drink products require some packaging, and the impact from production and consumption is causing a strain on the environment. To counteract the bad effects, business is emphasizing the environmental performance of products and therefore utilising Life Cycle Assessment as a tool to quantify the environmental impacts from a products life cycle. Elopak, which is an International supplier of paper-based packaging for liquid food, is a such company. This thesis is a Life Cycle Assessment focusing on an Elopak 1-liter beverage carton for fresh milk.

The main goal of this study is to quantify the environmental impact in a cradle-to-grave perspective. Also, to point out which life cycle phases that contribute most to impacts and to suggest strategies improving the system environmental performance. The product system is assessed in a European context and the reference time of primary data is set to the year 2015. Materials in the beverage carton consist mainly of liquid packaging board (LPB), and polyethylene (PE) for coating and closure. Important phases which are excluded from this study is retail and consumer activities.

Results from this study show an impact of 45 g CO_2 -eq for climate change, 57,7 mg PO_4^3- -eq for eutrophication, 79,1 mg NMVOC for photochemical oxidant formation and 154,6 mg SO_2 -eq for terrestrial acidification. The most contributing life cycle phases prove to be the production of raw materials in primary packaging where the impacts are dominated by the production of LPB and PE resins. Important strategies for improving the environmental performance of the product system is to ensure that raw materials have a low impact. This can be done by choosing environmentally friendly materials such as renewable plastics, reducing its weight and by improving production processes. Additionally, recycling should be encouraged to substitute the production of virgin materials.

Sammendrag

Bortimot alle mat- og drikkevareprodukter krever emballasje, og påvirkningen fra produksjon og konsumering av disse produktene fører til en belastning på miljøet. For å motvirke de negative effektene, har industrien satt fokus på at produktene skal være miljøvennlige, og i denne sammehengen benyttes livssyklusanalyse til å måle belastningen på miljøet. Elopak, som er en internasjonal leverandør av drikkekartong benytter seg av nettopp denne typen verktøy. Denne anhandlingen er en livssyklusanalyse (LCA) av en Elopak 1-liters melkekartong for fersk melk.

Hovedformålet med oppgaven er kvantifisere miljøpåvirkningen fra hele livsløpet til kartongen, peke på de prosessene som bidrar mest og foreslå strategier til forbedringer i produksystemet. Produktet er vurdert i en europeisk sammenheng hvor refeanse perioden for innsamlet primærdata angår år 2015. Kartongens viktigste materialer er papp og polyetylen. Plastikken brukes i korker og som et beskyttende belegg. Påvirkning fra aktiviteter relatert til salg i butikk og forbruker er ekskludert fra studien.

Resultatene fra studien viser en påvirkning på miljøet med 45 g CO_2 -eq for "climate change", 57,7 mg PO_4^3- -eq for "eutrophication", 79,1 mg NMVOC for "photochemical oxidant formation" og 154,6 mg SO_2 -eq for "terrestrial acidification". De viktigste prosessene med tanke på den negative miljøpåvirkningen er produksjon av råmaterialer for melkekartongen. Denne påvirkningen er dominert av produksjonen av pappkartong og plastikk i primær-emballasjen. De viktigste strategiene for forbedringer vil angå å senke den negative miljøpåvirkningen fra råmaterialene. Dette kan sikres vet å velge miljøvennlige materialer slik som fornybar plast, sørge for å minske materialbruken ved å senke vekten og å forbedre produksjonsprosesser.

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Appendix A: Environmental impact indicators

Appendix B: Mathematical operations in LCA modelling

Appendix C: Envrionmental impact results from literature

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Abbreviations

ACE	Alliance of beverage Cartons and the Environment
EPD	Environmental Product Decleration
GOs	Guarantees of Origin
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
LDPE	low-density polyethylene
LPB	liquid packaging board
NTNU	The Norwegian University of Science and Technology
PCR	Product Category Rule
PE	polyethylene
PET	polyethylene terephtalate
PHA	polycyclic aromatic hydrocarbons

1 Introduction

1.1 Context

The world's population has more than doubled over the past 50 years and is ever increasing. This population growth has led to a much higher production of goods and services, and the size of the global economy has grown from 1.35 trillion dollars in 1960 to over 70 trillion dollars now (The World Bank, 2015). This has further caused a strain on our environment because of the impacts from increasing emissions of greenhouse gasses, harmful particulates, and depletion of natural resources. As almost all types of goods require some packaging, the environmental impact from packaging is considerable and plays an important role (EUROPEN, 2011).

To cope with environmental problems caused by consumption, in 2015 the EU commission put forward a plan of action for a circular economy and a resource efficient development in Europe. The Circular Economy Package consists of few, but concrete measures connected to a circular economy (European Commissions, 2016). With its strong focus on downstream activities such as recycling, landfill and reuse, producer companies often ask for stronger focus on the whole life cycle of products. Regarding the environmental performance of packaging, end-of-life activities are important, but depending on the type of product, other parts of the life cycle can be just as important. Choice of packaging materials can provide a shift towards a carbon neutral and more environmentally friendly packaging sector, and packaging design can affect the overall consumption to avoid resource depletion in the long run. (Ruttenborg, 2016).

Life Cycle Assessment (LCA) has proven to be an important tool to assess the environmental performance of beverage packaging and is widely used to improve products, provide information to both customers and consumers and to also create a business advantage. By adopting this analysis tool, it is possible to quantify environmental impacts and to distinguish between the different contributing processes in the life cycle of each product (European Commission, 2010).

Today, the carton is widely used for beverage packaging and has proven to be the most environmentally friendly alternative.(Ruttenborg, 2016). Elopak is a global supplier of beverage cartons and has a strong focus on continuously improving its environmental performance through the entire value chain. The company has an ambitious vision to reach zero net impacts from their products and production processes. The latest improvement for Elopak beverage packaging is the implementation of a renewable plastic for closures and as a protective barrier, thereby substituting the former fossil-based plastics in their cartons (ELOPAK, 2014). In cooperation with Elopak and its suppliers, this master thesis will perform an LCA of fresh dairy packaging.

1.2 Research questions

The goal of this study is to conduct an LCA of an Elopak packaging product. The examined packaging system is a 1-litre standard carton for fresh dairy packaging. The mains questions which define the goal of this study are listed below, and further answered and discussed in Chapter 6.

1. By considering the entire life cycle, what is the environmental impact of an average Elopak 1 liter carton for fresh milk in a European context?
2. Which processes in the beverage carton life cycle contributes the most to the environmental impact, and what are critical variables?
3. What strategies could be appropriate to improve the product system environmental performance?

1.3 Structure of the report

This thesis is structured as a research report. In chapter 1, an introduction to the topic and research question are stated. In chapter 2, relevant literature is presented to provide background information for assessments of similar product systems. Chapter 3 describes the methodology which has been utilised for the literature study and the case-specific approach. Additionally, general LCA methodology is presented. Further, in chapter 4, detailed information about the product system under study and utilised data are presented separately. Results of the life cycle assessment are presented in chapter 5, with corresponding figures and detailed descriptions. The results also provide a sensitivity and a contribution analysis. The results are further discussed in chapter 6 concerning stated research questions, presented literature, uncertainties and further research. Conclusions which are based upon the discussion are presented in chapter 7.

2 Literature

2.1 Carton beverage packaging

Beverage cartons in general

Beverage cartons have become a popular and widely used alternative for beverage packaging. By using a multiple layer technology, the cartons protect freshness, flavours and nutritional qualities of the beverages during transportation and storage. The composition of beverage cartons are 75 % paperboard, 21 % polymers and 4 % aluminum on average and by weight (ACE, 2016a). The paperboard is made from wood pulp which has been bleached and washed to create a white surface before it goes into production. The wet pulp is then combined into multiple layers by a sophisticated control process to obtain high-quality paperboard. The most important parameters for high-quality paperboard are a smooth and white surface for good printability, correct bending stiffness, thickness and the ability to be cut and folded. To maintain stability, hygiene and protective properties in the beverage cartons it is coated by a PE layer on both sides. Cartons for light and oxygen sensitive beverages are protected by an additional aluminum layer. All parameters differ based on the needed functionalities of the beverage carton.

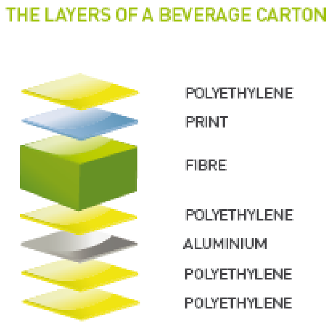


Figure 1: Illustration of carton layers

2.2 Existing LCA literature

A literature review was conducted as preparation for this MSc thesis to provide an overview of existing LCA literature, and the environmental impact from carton beverage packaging. The methodology is described in Section 3.1. The selected studies have been divided into two categories, "core" and "additional" literature. Selection process and literature criteria are further described in the methodology section. The studies which will be presented in this literature review is listed below in Table 1 and 2. Key elements of the core literature are summarised in Section 2.2.2, while the additional literature are briefly summarised in Section 2.2.3. Environmental impact results from both core and additional literature are further described in Section 2.2.4. The two Environmental Product Declerations (EPDs) from Elopak presented under additional studies are no longer available as they have expired.

Table 1: Overview of selected core literature

Title	**Researcher**	**Geographic Scope**	**Year**
Life Cycle Assessment of consumer packaging for liquid food LCA of Tetra Pak and alternative packaging on the Nordic market	IVL Swedish Environmental Research Institute	Nordic markets	2009
Nordic Life Cycle Assessment Wine Package Study	BIO Bio Intelligence Service	Norway and Sweden	2010
Comparative Life Cycle Assessment of beverage cartons combiblocSlimline and combiblocSlimline EcoPlus for UHT milk	IFEU The Institute for Energy and Environmental Research	Western Europe	2012
Life cycle assessment of example packaging systems for milk	WRAP The Waste and Resources Action Programme	UK	2010

Table 2: Overciew of selected additional literature

Title	Researcher(s)	Geographic Scope	Year
Carbon Footprint of Beverage Packaging in the United Kingdom	Gujba, H Azapagic, A	United Kingdom	2011
Elopak PE Coated Beverage Carton with Cap options	Atkins Ltd.	Europe	2013
Elopak Aluminium Coated Beverage Carton with Cap options	Atkins Ltd.	Europe	2013
The carbon footprint and energy consumption of beverage packaging selection and disposal	Pasqualino, J Meneses, M Castells, F	Spain	2011
Europe-wide life-cycle assessment of NCSD packaging systems	IFEU The Institute for Energy and Environmental Research	Europe	2010

2.2.1 Product specifications

The original scope of the literature study conducted as a preparation for this MSc thesis considered all types of carton beverage packaging regardless of beverage products. The literature study presented in this thesis examine three carton packages for milk and one for wine as core literature. The presented additional literature examine carton packaging for milk and juice. Dependent on the content in the cartons, different protective properties is required to maintain freshness of beverage products. Different properties require different materials in the protective layers of the carton, which can affect the environmental performance.

2.2.2 Core literature

System boundaries

The presented studies are all conducted in a European context where three of the four studies focus on specific markets such as the Nordic and UK market. The last study has a broader scope focusing on western Europe including the EU15 and Switzerland. Several of the investigated studies include packaging for many types of different beverages and in containers of different design, size and raw materials. In this summary of the four selected studies, the scope has been narrowed down to only consider 1,0-liter cartons. In a cradle-to-grave perspective, all processes in the life cycle of a product should be included in the impact assessment, however, in LCA, simplifications can be made to avoid uncertainties regarding data gaps. In studies including a comparison of similar products, simplifications can be made without affecting the relative performance between the products. As seen from these four studies such type of simplifications are made. In all studies, the most important processes are included from raw materials extraction, primary material production, beverage carton production and end-of-life activities. Processes regarding the beverage production, filling and customer activities are excluded due to either data gaps or for simplification reasons. The production, maintenance, and disposal of machinery and equipment are also pointed out to be excluded in two of the studies. An overview of excluded processes is provided below in Table 3.

Table 3: Overview of excluded processes in presented studies

Researcher	**Excluded processes**
IVL	Beverage production, refrigeration at retail and consumer, consumer transportation from retail.
BIO	Beverage production, infrastructure related, storage at distribution center and retail, consumer activities.
IFEU	Beverage production, infrastructure related, storage, packaging loss.
WRAP	Beverage production, ink and printing, consumer activites, packaging loss.

Differences in applied data

Data which has been applied to conduct LCA studies is a mix of primary data from producers, publicly available databases and specific inventory databases. Where data are missing or contain large uncertainties, general assumptions have been made. Data for conversion and coating of primary packaging and filling of beverages are provided by the commissioners and sponsors of the studies. These data is primary data sets from specific production sites. In the study conducted by BIO, primary data are provided by Elopak and Tetra Pak. Regarding end-of-life activities for this particular study, data is taken from national statistics of Norway and Sweden. For the other studies, these data are taken from the researcher's internal databases. In the case of the study conducted by WRAP, internal data are also mixed with confidential data provided by Tetra Pak. Transport data is a mix of pure assumptions, case-specific averages, and data from internal databases. In the BIO study, there has been adopted a specific transport model to take into account both weight and volume of the transported material.

Limitations and reliability

All LCA studies have limitations and uncertainties connected to its results because of the complexity of the product systems. Each of the presented studies is critically reviewed and approved to follow the correct methodology for international standards for LCA. Remaining limitations are connected to excluded processes, data gaps, assumptions, etc. In the IVL study, the product loss during transportation and production are excluded to avoid uncertainties when comparing systems. The intention of the WRAP study from the beginning was to cover average milk packaging systems on the UK market, but due to data gaps, this was not possible. To enhance the quality of the results, all studies have conducted a sensitivity analysis of the variables of high environmental significance. However, a direct comparison between similar product system must be done with caution because of the mentioned uncertainties, geographical differences and the time period of applied data.

2.2.3 Additional literature

The geographic scope for all studies is within the European boundary, where the Gujba and Azapagic (2011) study focus on the particular market of UK and the Pasqualino et al. (2011) study focus on the Spanish market. The two studies conducted by Atkins Ltd. for Elopak packaging are EPDs and consider only a cradle-to-customer-gate perspective. Rest of the studies consider the environmental impact from the entire lifecycle, but some stages are excluded, mainly the production of beverages and consumer activities. Production of beverage is included in Pasqualino et al. (2011). There are some differences between the containing beverages of the packaging. The Elopak EPDs have evaluated one carton for fresh milk and the other for juice drinks for long shelf life at room temperature. Further, the other studies also consider packaging for juice and milk where the intended freshness of the product determine the properties and thereby raw materials used in cartons. Table 4 show a summary of the additional literature.

Table 4: Summary of additional literature

Researcher(s)	Lifecycle perspective	Type of carton	Applied data	Reliability
Gujba et al.	Cradle-to grave	Juice and milk - properties not specified	Primary: Types and weights of packaging, energy consumption at filling. Secondary (Ecioinvent, ELCD, GaBi): Raw materials, energy, transport and waste management.	Published in The International Journal of Life Cycle Assessment.
Atkins Ltd	Cradle-to gate	PE coated beverage carton for fresh milk	Primary: Product specifications, Elopak production operations, transport, paperboard raw materials. Secondary: Plastic, other environmental impacts for paperboard, ink (Ecoinvent).	Published in compliance with The International EPD System.
Atkins Ltd	Cradle-to gate	Aluminium and PE coated beverage carton for long term shelf storage in room temperature	Primary: Product specifications, Elopak production operations, transport, paperboard raw materials. Secondary: Plastic, other environmental impacts for paperboard, ink (Ecoinvent), aluminium.	Published in compliance with The International EPD System.
Pasqualino et al.	Cradle-to grave	Aluminium and LDPE coated beverage carton for long term shelf storage in room temperature	Primary: Property analysis of carton products to obtain composition and weight of materials. Secondary: Environmental data for material consumption and emissions (Ecoinvent).	Accepted and published scientific article (Elsevier)
IFEU	Cradle-to grave	Carton packaging for juices, nectars and still fruit drinks.	Not specified	Critically reviewed to ensure the compliance with ISO 14040ff standard on LCA.

2.2.4 Environmental impacts

Core literature

The impact of raw material use and production of primary material of paperboard and closures are key contributors to the total environmental impact of cartons. For studies which include the benefit of carbon sequestration from the wood used to make cardboard, the impact is reduced. This leads to a much higher relative contribution from end-of-life process regarding climate change. In the case of the IFEU study, the end-of-life activities have the relatively largest impact to climate change and fossil resource depletion. A comparison of the environmental impact from the different studies has been made through normalisation of the presented results. The comparison is presented in Figure 2 and a description of the method is provided in Section 3.1.

As seen from the figure there are large differences in the results, which indicates that it is difficult to compare across LCA studies. The BIO study has a much higher impact on global warming, acidification, eutrophication, human toxicity and abiotic resource depletion relative to the compared studies. This is the only study which examines packaging for wine, and the properties of the packaging layers are different than for the milk packaging alternatives. A thin aluminium foil layer provides an extra oxygen barrier for the wine beverage to provide a long shelf life in ambient temperature. The high impact to human toxicity is related to polycyclic aromatic hydrocarbons (PHA) emissions, a substance which is emitted during aluminium production. The total weight of the carton is also higher than for the milk cartons, which indicates more raw materials per volume of beverage, and thereby greater environmental impact. In the WRAP study, the results for milk packaging show a high impact compared to the other literature in photochemical oxidant formation. About 60-70 % of the impact is caused by laminate and cap production, where laminate production is predominant. Distribution transport and packaging cause 15-20 %. Even though the WRAP study includes a doorstep delivery system, the more than doubled impact to photochemical oxidant formation is not directly caused by this, and the main contributor is difficult to point out.

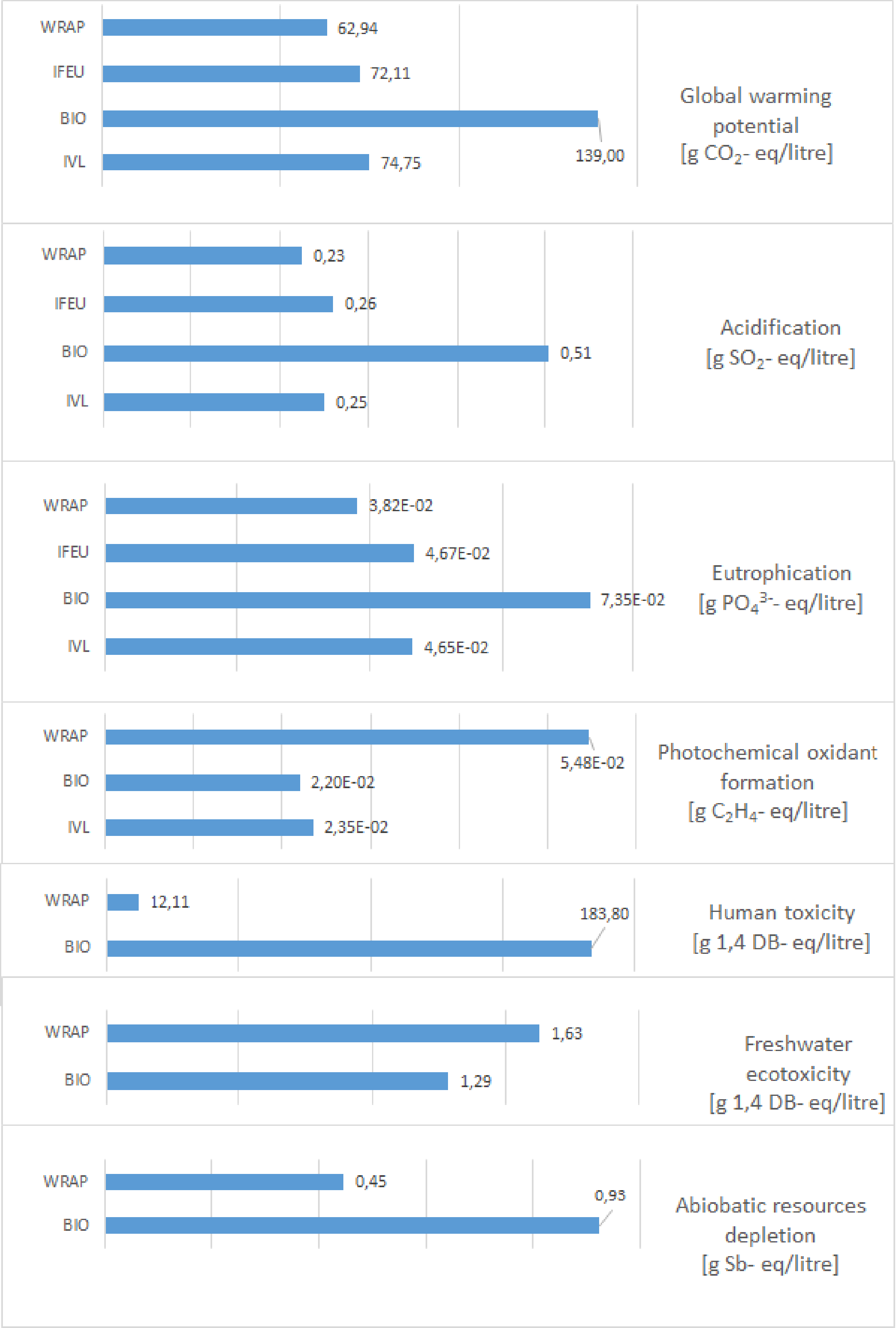


Figure 2: Comparison of cradle-to-grave environmental impacts for core literature

Additional literature

The Global Warming Potential (GWP) for additional literature is shown in Figure 3. The EPDs from Atkins Ltd. for Elopak cartons show a large difference between the two carton products by almost 70 % higher impact from the aseptic carton. The most contributing process for the aseptic carton is the extraction of raw materials and production of the aluminium barrier, by 26 % of its total impact to GWP. For the PE coated beverage carton, production of paperboard is the most contributing process. There is a significant difference between the three cradle-to-gate studies, showing an impact to GWP from 87-113 gram $C0_2$ equivalents. One of the obvious reasons for this is that beverage production is included for Pasqualino et al. (2011), but not for the two other studies. Credits for end-of-life savings from recycling are accounted for in IFEU (2010) and Pasqualino et al. (2011), but not for Gujba and Azapagic (2011). Another indicator of the large difference could be that wood used to produce paperboard is considered carbon neutral in the IFEU study. The paperboard is also produced with an electricity mix containing more than 90 % renewable energy. In all of these three cradle-to-grave studies, the raw material extraction for primary packaging production is the hot spot of the total carbon footprint.

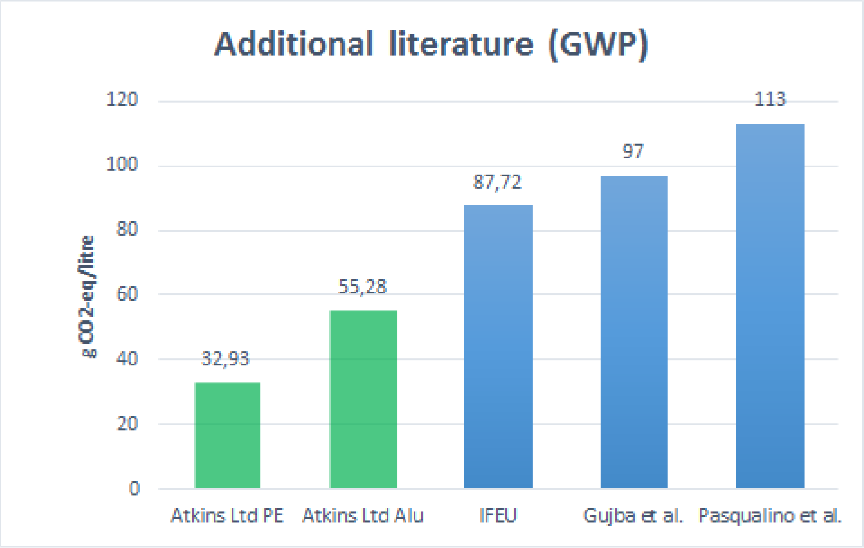


Figure 3: Comparison of GWP impacts for additional literature

3 Methodology

3.1 Literature review: Criteria and research methods

A literature review was conducted as preparation for this LCA of beverage cartons at Elopak, and a summary of the most important and relevant studies will be presented to provide an overview of existing literature. The criteria for the selection of studies is relevant to the system boundary of the LCA. The chosen studies have been conducted within the last ten years in a European context. The impact assessment for the core studies covers the whole life cycle in a cradle-to-grave perspective providing quantitative results for comparison purposes. Additional studies are also presented such as EPDs which covers a cradle-to-gate perspective. The results also cover other impact categories in addition to GWP and distinguish between the different processes in the lifecycle of the products. For the additional literature, the environmental impact results will focus on the GWP only.

To be able to gather relevant literature on this topic, available databases for scientifically published material was accessed. Several databases provide advanced search engines for electronic and printed collection of books, articles, journals, master- and doctor theses. Example for the databases which has been used are Scopus, Google Scholar and The Norwegian University of Science and Technology (NTNU) own Oria. Scopus is the largest search engine for abstracts and citations of peer-reviewed literature and provides a quality assurance of all search results (Elsevier, 2017). All gathered literature were organised in an excel document, and an illustration of the selection process is provided in Table 5.

A comparison of the environmental impacts from the selected studies has also been made. The comparison show results for 1,0-liter packaging alternatives from each study. The comparison has been made for all impact categories where a minimum of two studies cover each category. The results have been gathered in an excel file and normalised to show the results in grams of category-equivalents per 1,0-liter package. The data basis for the comparison can be viewed in Appendix C: . Results from the IVL study only show a bar graph example from the original study. Data have been extracted from graphs of the original study to make a data basis for the other impact categories, but these graphs are not provided in this report.

Table 5: Example of selection process for literature. Red=excluded literature, yellow=additional literature, green=core literature. Grey colour indicates elements that deviate from scope.

Author	**Type of study**	**Product(s)**	**Geo Scope**	**Included lifecycle steps**
Mourad, A. L. Da Silva, H. L. G. Nogueira, J. C. B.	LCA	Carton	Brazil	Cradle to gate
Atkins Ltd	EPD	Carton	Elopak's European Operations	Cradle to gate
Jelse, K Eriksson, E Einarson, E	LCA	PET and Carton	Nordic market	Cradle to grave

3.2 LCA - a brief introduction

LCA is a structured, comprehensive and internationally standardised method, which is developed with the purpose to understand better and to address the environmental impacts related to products, processes and services. The main objective of performing an LCA is to create a consistent comparison of technological systems on their environmental impact (Strømman, 2010). This is done by quantifying emissions and resources consumed which is relevant to the studied system, and the related health impacts and resource depletion issues. Further, the LCA method can assist in (Finkbeiner et al., 2006):

(1) identifying opportunities for potential improvements of environmental performance

(2) informing decision-makers to enhance strategic planning processes, priority setting and product design in industry, government and non-govenrment organizations

(3) the selection of relevant indicators and measurement techniques of environemental performance

(4) create ecolabelling schemes, environmental claims or producing EPDs.

LCA takes into account the full lifecycle of products from resource extraction, through production, use and recycling, up to final disposal. It can be applied to many different business sectors such as construction, transportation, energy, waste treatment, packaging, etc. (Pasqualino et al., 2011). As described in the international standard for life cycle assessment, Finkbeiner et al. (2006), LCA is an iterative process consisting of the four stages illustrated in Figure 4. **The goal and scope definition** describes the intention and the reason for carrying out the study. In addition, the boundaries of the product system is described along with the functional unit, allocation methods, assumptions and limitations related to the study. **Life Cycle Inventory analysis (LCI)** involves the collection of data for physical flows within the product system. Flows are calculated to be quantitatively related to the functional unit.

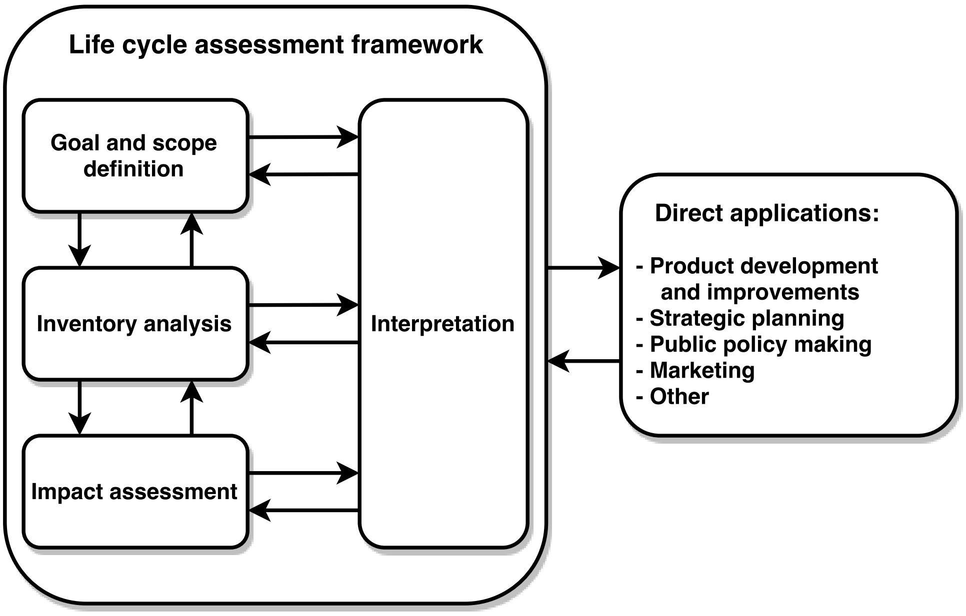


Figure 4: Stages of an LCA(Finkbeiner et al., 2006).

To quantify potential environmental impacts a **Life Cycle Impact Assessment (LCIA)** is performed. The process is illustrated in Figure 5 and the first step involves the selection of impact categories, category indicators and characterization models. The next step is to assign the LCI results to the chosen impact categories and to calculate the related category indicator results. Interpretation and possible adjustments must be made along the entire LCA process (Finkbeiner et al., 2006).

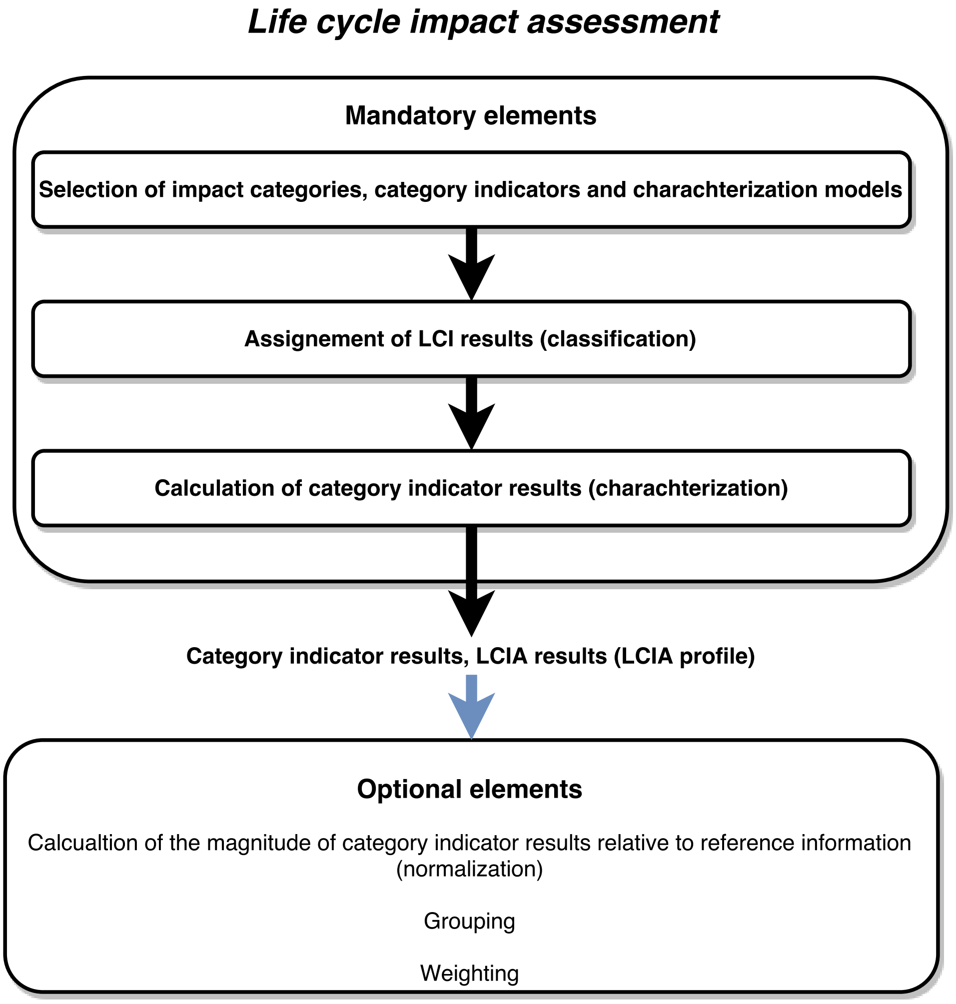


Figure 5: Elements involved in LCIA (Finkbeiner et al., 2006)

Attributional and consequential LCA

The two main modelling principles which are in use in LCA practice are attributional and consequential modelling. They represent two fundamentally different situations of modelling the analysed system. Attributional modelling depicts the environmental impacts which can be attributed to a system over its life cycle. Consequential modelling is a "change-oriented" method where the aim is to identify consequences of decisions in the foreground system to other processes and systems of the economy (European Commission, 2010).

3.3 Case specific- and calculation methods

The methodology which has been used to collect, process and perform this study will be described in this section.

3.3.1 Research methods and workflow

This study was started as a follow-up of a literature review of carton beverage packaging, and the comparison to polyethylene terephtalate (PET) bottles. Together with the supervisor at NTNU and Elopak, research issues for this study was formed. The assignment which was planned in an early stage required data collection from different Elopak suppliers. The contact with suppliers was supervised by Elopak. Elopak provided primary data for Elopak processes in the lifecycle of the product. In parallel with the collection of primary data, relevant literature for life cycle assessments of beverage packaging was adopted into the report from previous work.

Primary data was collected and organised in excel files. As this study consider average packaging for fresh milk, weighted averages of carton specifications based on sales for 2015 was calculated and prepared as an input to the system model. As data from an Elopak supplier was not available, changes to the original case had to be made. Instead of considering two products, this study was modified to consider one product system. Complete life cycle inventories were not available for all stages of the product life cycle. Therefore, different types of data have been applied to this study. For instance, generic data from the Ecoinvent database have been implemented for waste management activities, adjustments of "outdated" datasets have been made by utilising more recent reports, and environmental impact results from published EPDs have been applied in the case of LPB production and electricity consumption in beverage carton production. The poor resolution of the collected data from EPDs would lead to limitations in the impact assessment. Hence, two different data scenarios were applied to both utilise the most recent data and to provide a complete impact assessment considering all impact indicators in the ReCiPe method.

A visit to Tine dairies was made to acquire information about the forming and filling stage.

The complete process of carton preparation and filling of milk product was inspected. The experience was adopted into the analysis together with additional information for inputs used in the filling process and packaging used in the distribution phase.

3.3.2 Frameworks

This study follows the requirements stated in Finkbeiner et al. (2006), the international standard for life cycle assessment. Product Category Rule (PCR) is a more specific framework for LCA (ACE, 2015), which follow the ISO Standard for carton beverage packaging. The framework is a guidance for performing LCAs to be verified as a EPD by the International EPD system. This study has applied this methodology to provide consistent results and to apply the ISO standard specifically for carton beverage packaging.

3.3.3 Scenario creation

Elopak makes use of different suppliers for LPB utilised in beverage cartons. To be able to apply case-specific data, different EPDs for LPB have been applied as a data basis. Reconstruction of the environmental impacts from the EPDs by using listed inputs and outputs of energy and material resources was not possible. Instead, the environmental impact results were extracted, as midpoint indicators, and utilised in this study. This implies that background processes for LPB production are not included, and results are limited to only consider impact categories which are included in the EPDs. A EPD has also been used for impacts from electricity consumption in beverage carton production. Elopak utilises electricity with a Guarantees of Origin (GOs) of hydropower in production factories.

As a consequence of the limitations mentioned above, two scenarios have been created, one by using case specific data from a EPDs, which in this study will be called the "base scenario", and one by using generic data from the Ecoinvent database. The generic data scenario is created to provide results including all impact indicators in the ReCiPe method, which is applied in this study. The effect on the environmental performance of the system by using different data basis is also tested. The two scenarios which will be tested are:

Base scenario: Utilising case-specific data for LPB production and electricity in beverage carton production.

Generic data scenario: Utilising generic data for LPB production and electricity in beverage carton production.

All other data are similar in both scenarios.

3.3.4 Adjustment of LCI data for plastics production

Data which have been applied for the production of plastic resins, high-density Polyethylene (HDPE) and low-density polyethylene (LDPE), are based on Ecoinvent 2.2. In this study, these data have been updated by using PlasticsEurope (2014). In the case of different units, characterization factors for the ReCiPe method have been applied to make results consistent.

3.3.5 Primary data calculations

Primary data from Elopak consist of specific production, transport and sales numbers in 2015. It includes all types of Elopak 1 litre carton packaging for fresh milk, its production, transport and secondary and tertiary packaging. Data which has been utilised in this study are the weighted average by production and sales volume in Europe. The only exception from the European boundary is a producer of plastic closures and the transportation. The exception is made because of its significance for sales in Europe. All inputs and outputs from the system are calculated based on requirements of the functional unit. For the converting process, process specific inputs and outputs are allocated by area of produced packaging material, as described in ACE (2015).

3.3.6 End-of-life impacts and benefits

Credits have been attributed to the system based on the methodology described in ACE (2015). A simplification has been made regarding secondary and tertiary packaging, where the method applied in this study is similar to both primary, and secondary and tertiary packaging. Impacts related to collection, sorting and transportation to waste management facility is included in all end-of-life routes. Also, impacts from the landfill and incineration processes are included. Benefits from waste management are described below.

Recycling

Credits are attributed to the system for recovered materials in recycling processes. For recycling of liquid packaging board and cardboard and paper, impacts from the production of "wellenstoff" (recovered fibre-based fluting) from recycled fibres are attributed to the system as credits. Plastic fractions in primary packaging are assumed to be sent to incineration, where credits are given for recovered energy. This is further described below. Recovery of plastics in secondary and tertiary packaging is substituted by the production of virgin plastic resins. As recycling of materials causes a loss of the materials original qualities, substitution factors have been applied. The factors are based on an unpublished background study for an Elopak EPD. The factors are listed below:

- Paper fibres (LPB, paper wrap, cardboard): 0,9
- Pastics (LDPE film): 0,94

Incineration

Credits are attributed to the system for recovered energy in the form of heat and electricity. The amount of recovered energy per kilogram of waste is based on net recovered electricity and heat from the incineration process reported in the Ecoinvent 2.2 process. Recovered electricity is substituted by the production of average virgin electricity on the European market, without distribution and transformation losses. The process has been modelled by Ecoinvent 2.2. As there is no process in Ecoinvent for the production of district heating, a district heating mix has been created based on average inputs in European district heating, taken from Eurostat statistics(Eurostat, 2015a).

Landfill

Production of energy from recovered landfill gas is given as credit to the system. This is only related to decomposition of paper and cardboard. Electricity and heat recovered per kilogram of waste are based on data reported in Ecoinvent 2.2 process. Credits attributed to the system from recovered heat is modelled by impacts from a natural gas boiler. Recovered electricity follow the same methodology as for incineration.

3.3.7 Biogenic carbon

Biogenic carbon emissions and sequestration are integrated and accounted for in Ecoinvent processes which have been utilised in this study. This is related to incineration of waste, landfill, burning of wood and other activities regarding plant-based materials.

3.3.8 Allocation methods

In the Finkbeiner et al. (2006) standard for LCA, allocation is defined as partitioning input or output flows of a process or a product system between the product system under study and other product systems.

Carton converting and coating process: Inputs and outputs from this process are allocated by area of produced packaging material.

Waste management: Impacts attributed to the system follow the "Polluter Pays allocation method". Impacts related to collection, sorting and transportation of waste is allocated to the system under study. So are impacts related to landfill and incineration processes. Recycling of materials is allocated to the recovered product, which implies that impacts are excluded from this system. Credits are attributed to the system for recovered materials and energy.

3.3.9 Life cycle impact assessment

The most important steps which have been performed to calculate the category indicator results presented as final results for this study are described in section 3.2. The system has been modelled by using the ReCiPe method (Goedkoop et al., 2009). In this study the midpoint method has been chosen, which is proposed as the baseline method for characterisation in the Handbook of LCA (European Commission, 2010). In the ReCiPe methodology, uncertainties have been incorporated in the form of different perspectives. Three perspectives are presented, Individualist, Hierarchist and Egalitarian. In this study, a Hierarchist perspective has been chosen, which is based on the most common policy principles related to time-frame and other issues. Four impact indicators are presented for the base scenario and have been emphasised in this study. A presentation of these four indicators is made in Appendix A: . In the generic scenario, all impact indicators in the ReCiPe method are presented. The contribution analysis has been performed for indicators which are most relevant concerning beverage packaging. Mathematical operations in life cycle impact assessment can be viewed in Appendix B: .

3.3.10 Interpretation methods

The interpretation of the provided results in this study is supported by a comparison of scenarios, a contribution analysis and a sensitivity analysis.

3.3.11 Modelling software

Collected data for modelling of the product system have been organised i excel files. Further, modelling has been performed with the Arda calculator (version 1.8.2), with Ecoinvent (version 2.2)(Ecoinvent, 2017) as background database and calculations which follow the ReCiPe methodology (version 1.08)(Goedkoop et al., 2009). The Arda calculator is developed by researchers in the Programme of Industrial Ecology at the Norwegian University of Science and Technology in Trondheim.

4 Product System and Inventory Analysis

4.1 Functional unit

The main function of the product under study is to protect the containing beverage from any damage to its freshness until final consumption and to provide information to the consumer by its printed surface. The functional unit is:

- *The packaging required to store and protect one litre of fresh milk until point of consumption.*

The functional unit is the reference flow for all other flows within the product system. This includes materials, energy, transport, etc.

4.2 System boundaries

4.2.1 Geographical and time related scope

The product system in this study is evaluated in a European context. Primary data consider Elopak activities within the European border, except one cap producing facility and its transportation into Europe. Reference time for primary data relating the product under study and core processes is based on production and sales in 2015.

4.2.2 Lifecycle phases

This study evaluates the product in a "cradle-to-grave" perspective. This includes processes from the extraction of raw materials until the point disposal and waste treatment. According to ACE (2015) retail and consumer activities are assumed to be attributed to the milk product and therefore have been excluded from this study. Refrigeration during distribution and loss of materials at carton production is also excluded from the study. Production and maintenance of machinery are not included in primary data. The included life cycle phases in the product system are presented in Figure 6 and briefly described in this section.

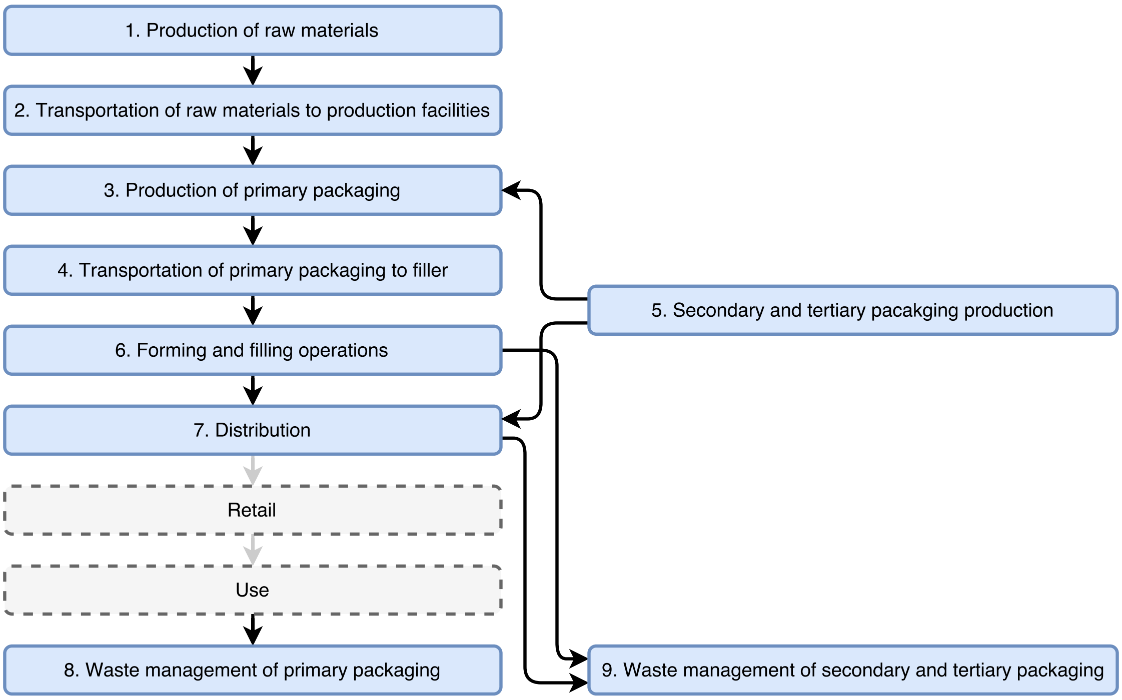


Figure 6: Life cycle phases in the product system. Excluded phases in grey

1. Production of raw materials

This phase consists of the extraction of natural resources and other activities necessary to produce liquid paperboard, plastic caps, plastic resins for beverage carton coating, and printing ink.

2. Transportation of raw materials to production facilities

The transport of all materials mentioned in phase 1, which are needed for primary packaging production. It also includes the transportation of secondary and tertiary packaging from factory gate to the point of use.

3. Production of primary packaging

The core production of Elopak consist of coating and converting of liquid paperboard into printed blanks. The printed blanks are further prepared with transport packaging.

4. Transportation of primary packaging to filler

Printed blanks and caps are transported from carton production to filling facilities.

5. Secondary and tertiary packaging production

The extraction of raw materials and the production of corrugated box, paper wrap, plastic wrap, pallet and roll container.

6. Forming and filling operations

Blanks are formed into cartons, filled with drink product and sealed with a plastic cap. The production of drink and cooling of the finished product is not included in the study.

7. Distribution

The finished beverage carton is loaded on to roll containers and prepared for distribution. This stage includes the transport and the secondary packaging required for transportation. The weight of the drink product is not included, neither is refrigeration.

8. Waste management of primary packaging

This phase considers the end-of-life activities for the beverage carton and its materials. It includes the transport of waste from the collection point, treatment and potential transformation into secondary products. Chosen end-of-life routes are recycling, incineration with energy recovery and landfill. Credits for recovered energy and materials are given to the system. Calculation methods follow ACE (2015). Calculation methods are described in Section 3.3.6.

9. Waste management of secondary and tertiary packaging

End-of-life activities for all materials of secondary and tertiary packaging. Processes are the same as for primary packaging as explained for phase 8. Credits are given accordingly.

4.3 Packaging specifications and system flowchart

4.3.1 Carton

Product specification of the beverage carton, closure and transport packaging, except distribution packaging to retail, are based on data for products sold in the year 2015. The carton specifications presented represents an average Elopak 1-liter carton of fresh milk.

Table 6: Carton specifications. Grams per functional unit.

Item	**Type of material**	**Weight of element (g/FU)**
Carton	Liquid packaging board	23,1
	Coating (LDPE)	3,1
Closure	HDPE	1,4
	LDPE	1,4
Total weight	***Carton and closure***	***29,0***

4.3.2 Secondary and tertiary packaging

Table 7 present the specification for the secondary and tertiary packaging used in the model. Secondary and tertiary packaging have only been assumed for transport of coated blanks from Elopak production units to filler, and from filler to retail. Packaging for transport of raw materials has not been included due to lack of data. Packaging for transportation from Elopak production units to filler are based on primary data from Elopak, while packaging for transportation from filler to retail are based on data from (WRAP, 2010).

Table 7: Specifications for secondary and tertiary pacakging

	Material	**Number of FU per unit**	**Unit weight (g)**	**Weight per FU (g/FU)**
Secondary packaging	Paper Wrap	225	60	0,27
	Corrugated box	450	305	0.68
Tertiary packaging	LDPE Wrap	-	-	1.69x10^-5
	Wooden pallet	22500	22500	1
Distribution	Roll container	160	38,000	237.5

4.3.3 System flow chart

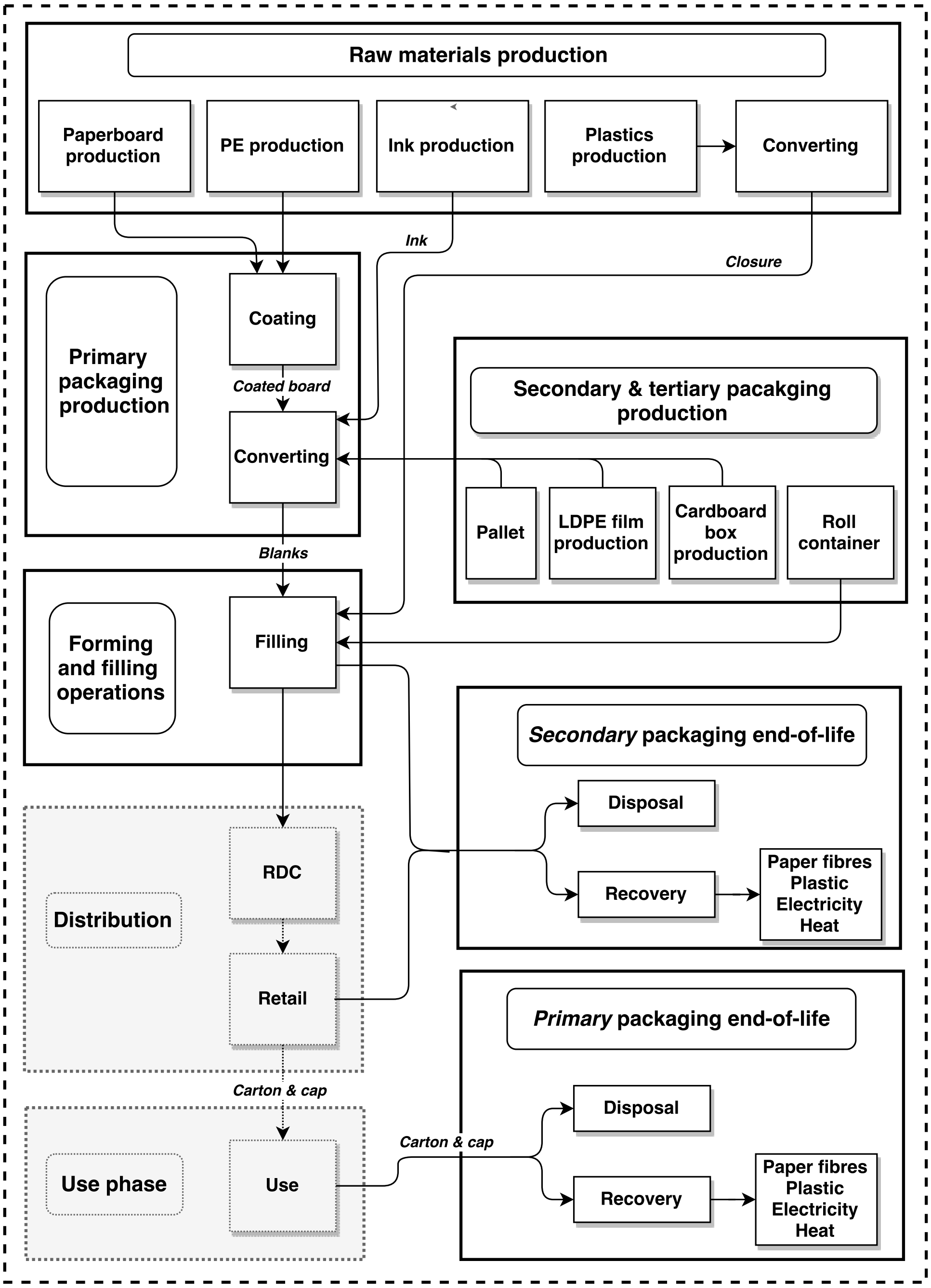


Figure 7: Flow chart for product system

4.4 Lifecycle inventory analysis

4.4.1 Main datasets used in this study

The data which has been used in this study is a mix of primary data provided by Elopak, generic data from Ecoinvent databases, experience from industry visits and literature data. A list of utilised data and its origin is presented in Table 8 . Two scenarios have been created based on different data for the same processes. In scenario two, data based on the two EPDs for the production of liquid packaging board, and the electricity utilised in production, has been replaced by generic data from Ecoinvent 2.2 to be able to perform a full impact assessment for all impact categories.

Table 8: Main data sets utilised in this study

Process	**Data source**	**Reference period**
Liquid packaging board	Environmental product declerations published by Elopak suppliers	-
Plastic resins production (HDPE, LDPE)	PlasticsEurope Eco-profile	2011
Coating and coverting of liquid packaging board	Primary data provided by Elopak (confidential)	2015
Carton filling	Primary data provided by Elopak (confidential)	2014
Transport	Primary data provided by Elopak (confidential)	2015

Table 9: Ecoinvent data sets utilised in generic scenario

Scenario datasets from Ecoinvent 2.2	**Time period validity**
Liquid packaging board	Europe (RER), 1993-2000
Electricity	Europe (RER), 1992-2004
	Sweden (SE), 1992-2004
	Finland (FI), 1992-2004

4.4.2 Production of liquid packaging board

For the production of liquid packaging board used in Elopak beverage cartons, data are based on different suppliers. As primary LCI data from production was not available, data has been based on EPDs for liquid packaging board. Due to problems of reconstructing actual environmental impact reported in the EPDs by using inputs and outputs of material and energy sources from these reports, only presented midpoint indicators of the environmental impact have been extracted and used in this study. To be able to evaluate all impact categories, an additional second scenario has been considered by using generic data from Ecoinvent database which represent average production of liquid packaging board in Europe.

The environmental impact results in the two EPDs are separately reported in upstream-, core and downstream impacts. Downstream impacts take into consideration the transport of the liquid packaging board to an average customer. This step has been excluded from the EPDs to apply primary transport data reported by Elopak.

4.4.3 Manufacture of plastics

Production of plastic materials is based on data from Ecoinvent version 2.2. These data originate from the PlasticsEurope eco-profile. The dataset in Ecoinvent version 2.2 is an older version of the eco-profile, and an updated version of the data is publicly available in the PlasticsEurope database. To be able to utilise the most recent data, the Ecoinvent dataset has been updated by using environmental impact results from Plastics Europe EPD (PlasticsEurope, 2014). In this study, data for HDPE and LDPE have been used.

Processing of plastic by injection moulding of plastic caps and extrusion of plastic film has been modelled by using Ecoinvent 2.2 data sets.

4.4.4 Printing ink

Data for the ink used in the printing of beverage cartons are taken from Ecoinvent database. The dataset includes the extraction of raw material, their transportation and the energy use during production. No process emissions are considered. The process output is printing powder without any cartridges located at the production plant. No transportation beyond production is included in this data set.

4.4.5 Production of beverage carton

The production of beverage cartons includes the processes of coating and converting. Primary data has been provided by Elopak, and an average of the European production has been used in this study. The data includes energy consumption of different energy fuels related to the area of packaging cartons produced in the year 2015. Electricity for carton production in Elopak factories is bought as GOs from Norwegian hydropower. Data for impacts are extracted from Østfoldforskning (2013). Transformation and distribution losses are not included in the EPD, but has been included based on recommendations in the EPD for medium voltage.

4.4.6 Secondary and tertiary packaging

Elopak provides data for the production of secondary and tertiary packaging for transport of coated board to fillers. The configurations of the packaging are reported as weight of each packaging type per functional unit. Transport packaging type from filler to distribution HUB and retail are based on industry experience from a visit at Tine dairies in Trondheim, and the configurations are based on data from WRAP (2010). No packaging for the transportation of raw materials to beverage carton production has been included in the study due to lack of data.

4.4.7 Forming and filling

The data which has been included for the forming and filling process of cartons are the specific energy consumption, chemicals and water use by filling machines at Tine dairy in Trondheim. No data for other activities at filler has been included due to lack of data. Elopak provided the technical data. In the filling process, a loss of 1% of the cartons is assumed due to quality assurance of the drink product. Roughly the same amount of cartons is lost in the startup of each filling process, but the number of cartons filled in each cycle is highly variable. This information was obtained at an industry visit at Tine dairies in Trondheim.

4.4.8 End-of-life settings

The amount of packaging waste is based on the weight of the original packaging. No loss is assumed. End-of-life routes for primary packaging have been modelled based on statistics from Alliance of beverage Cartons and the Environment (ACE) (ACE, 2016b). For secondary and tertiary packaging statistics from Eurostat has been applied (Eurostat, 2015b). Data are European average of household waste fractions relevant for this study. All waste are either treated by recycling, incineration with energy recovery or landfilled with the utilisation of the captured landfill gas. Credits are given to the system for recovered material and energy. The methodology used for impact and credit calculations follow ACE (2015) and is fully described in Section 3.3.6. All waste processes are taken from Ecoinvent 2.2. Statistical end-of-life rates used in this study is presented in Table 10.

Table 10: End-of-life settings for all packaging

	Recycling	**Incineration with energy recovery**	**Landfill**	**Reuse**
Carton	44%	30%	26%	-
Paper wrap and cardboard box	82,2%	7,9%	9,9%	-
Plastic wrap	37,7%	30,8%	29,5%	-
Pallet	-	100%	-	23 times
Roll container	-	-	100%	500 times

4.4.9 Transport

The transport settings are based on primary data provided by Elopak, assumptions and average transport data in Ecoinvent processes. Elopak data includes transport by truck, train and ship. All other transport is assumed to be by truck. Transportation alternatives have been modelled by Ecoinvent 2.2 which takes into account the distance and the weight of the transported product. Table 11 provides an overview of the different transport steps in the system, which element that is transported and the distance used in the model. Assumptions are based on data from the PCR.

Table 11: Transport settings

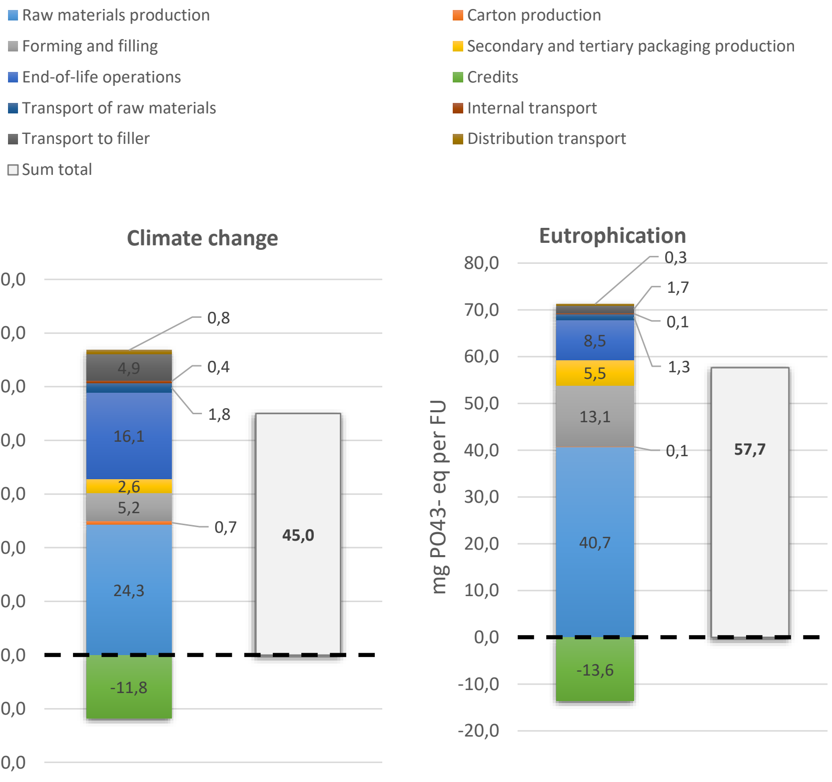
Transport stage	**Material**	**Distance**
Raw materials to carton production	LPB, plastics, cardboard box, paper wrap	Primary transport data for 2015
	Ink, pallet, roll container	400 km (assumption)
Elopak internal transport	Coated board, raw materials	Primary transport data for 2015
From carton and cap production to filler	Carton, cap	Primary transport data for 2015
Distribution	Filled carton in roll container	160 km (assumption)
To waste facilities	All items	400 km (assumption)

5 Results

In this chapter, the results of the environmental impact assessment are presented. It includes results for the two scenarios presented in Section 3.3.3, interpretations and a comparison of coinciding impact categories for the two scenarios.

5.1 Base scenario

The absolute and relative results for the base scenario is presented below in Figure 7 and 8. These figures include the contribution from each lifecycle phase to impact categories, together with the total lifecycle impact presented as a separate bar graph. To pinpoint which processes that contribute to production of raw materials, secondary and tertiary packaging and transportation, more detailed information is provided in figure 9. The relationship between end-of-life impacts and credits is presented in figure 10. Four impact categories are presented for this scenario; climate change, eutrophication potential, photochemical oxidant formation and terrestrial acidification.



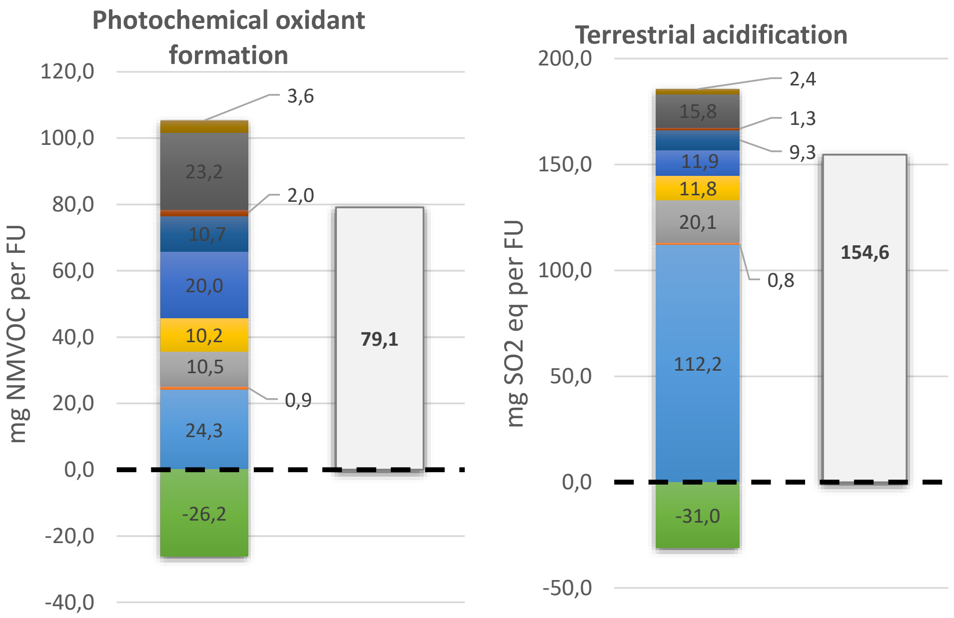


Figure 7: Life cycle impacts for base scenario. Grey bar shows the total impact when credits are subtracted.

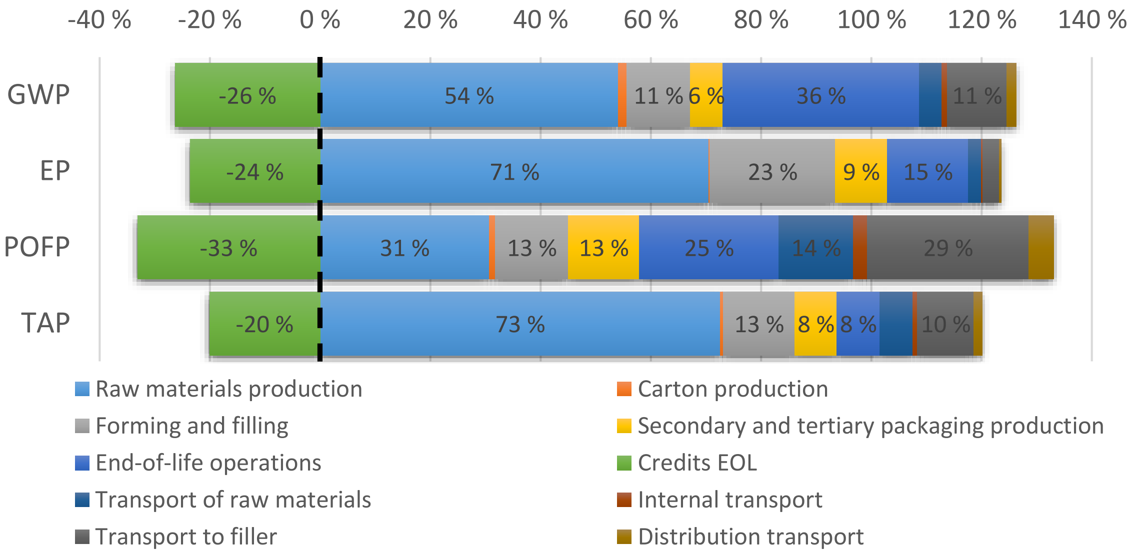


Figure 8: Breakdown of relative impacts for base scenario[1].

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[1] GWP: Climate change, EP: Eutrophication, POFP: Photochemical ocxidant formation, TAP: Terrestrial acidification

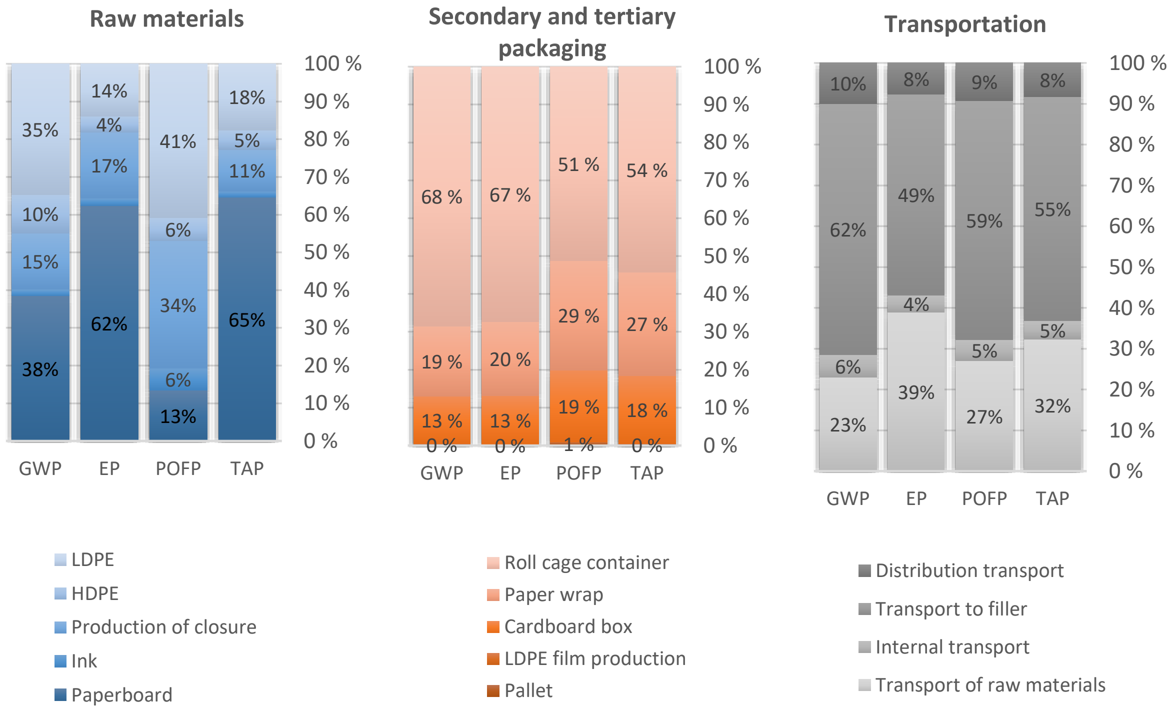

Figure 9: Breakdown of relative impacts for raw materials extraction, secondary and tertiary packaging production and transportation. For production of closure, only process impacts are included, not raw materials. All plastic raw materials are included in "LDPE and "HDPE"

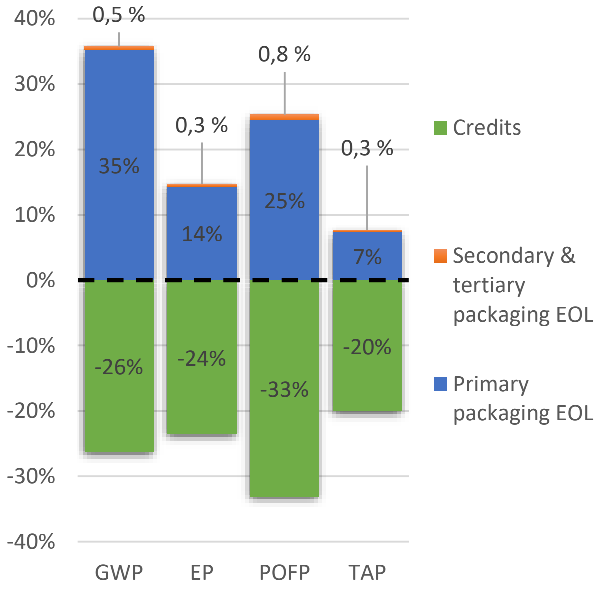

Figure 10: Comparison of waste management impacts and attributed credits in base scenario

5.1.1 Description of results

The main contributing process to the environmental impact is the production of raw materials, with an average of 57% of the total impact across all categories. For photochemical oxidant formation, transport to filler and end-of-life operations also have a considerable impact on the total lifecycle impact. These three phases account for 85% of the total impact in this category. The 2nd largest contributor to all categories, is waste management with an average of 21% lifecycle impact.

Production of raw materials

In this lifecycle phase, the production of paperboard for the beverage carton is the dominating process of eutrophication and terrestrial acidification, by its 62% and 65% contribution to the total impact. It also has the highest impact on climate change, but if production of LDPE and HDPE resins are added together, it accounts for 45% of the impact, which is higher than for LPB (38%). For photochemical oxidant formation, the production of LDPE resins for coating and closures and the injection moulding of closures have the highest impact. This is the only indicator where paperboard production does not have a significant contribution. Even though the impact of LDPE resins has a twice as high impact to POFP compared to HDPE (PlasticsEurope, 2014), the main reason why LDPE has a 7 times higher impact than HDPE in this study is the difference in the amount of raw materials used. HDPE is only used for caps, while LDPE is used in caps, coating, plastic film and roll cage wheels. LDPE has also a significant impact on climate change by 35%.

Secondary and tertiary packaging

The roll container used in the distribution of the final drink product has the highest impact in this phase to all impact categories by an average of 60%. The contribution comes from the production of steel which is the main material. The second largest impact on all categories comes from the manufacture of the paper wrap. This includes both the extraction of raw materials, such as forestry and the production of paper. For the LDPE film production, only process impacts are considered. Impacts from plastic raw materials are aggregated into raw materials production.

Transportation

Transport to filling has the highest impact in all categories compared to the other transport stages. The distance for this stage is an assumption of 160km, based on the PCR. The transport accounts for both the distance and the weight of the transported product. As the distribution of the finished drink product includes both the weight of the primary packaging and the roll container, which has a relatively excess weight per functional unit, a considerable impact is to expected. The second largest contributor, also with a significant impact, is the transport of raw materials. This stage includes several different products transported from various locations to the carton production facilities. Average contribution for the two mentioned transport stages is 56% and 30%.

End-of-life impacts and credits

The comparison of lifecycle impacts from waste management versus credits related to these activities shows that the credits outweigh impacts in 3 out of 4 impact categories. For terrestrial acidification, the attributed credits is almost three times higher than the impact. The majority of the credit given to the system is related to the recovery of paper through recycling of primary packaging cardboard. The most important impact related to waste management is the fraction of primary packaging sent to landfill, and for climate change, there is a considerable impact from incineration of the plastic fraction in primary packaging.

5.2 Generic data scenario

In this scenario, generic data has been applied for production of liquid packaging board and electricity consumption in carton production. The reason for this is to provide complete results including all impact categories. This is further described in Section 3.3.3. Relative results is presented in Figure 11 for all impact categories. Absolute results are summarised in Table 12, and a comparison of waste management activities and credits attributed to the system is presented in figure 12. A comparison of coinciding impact categories for the two scenarios is performed in Section 5.3, specifically for total lifecycle impacts, production of LPD and production of beverage cartons.

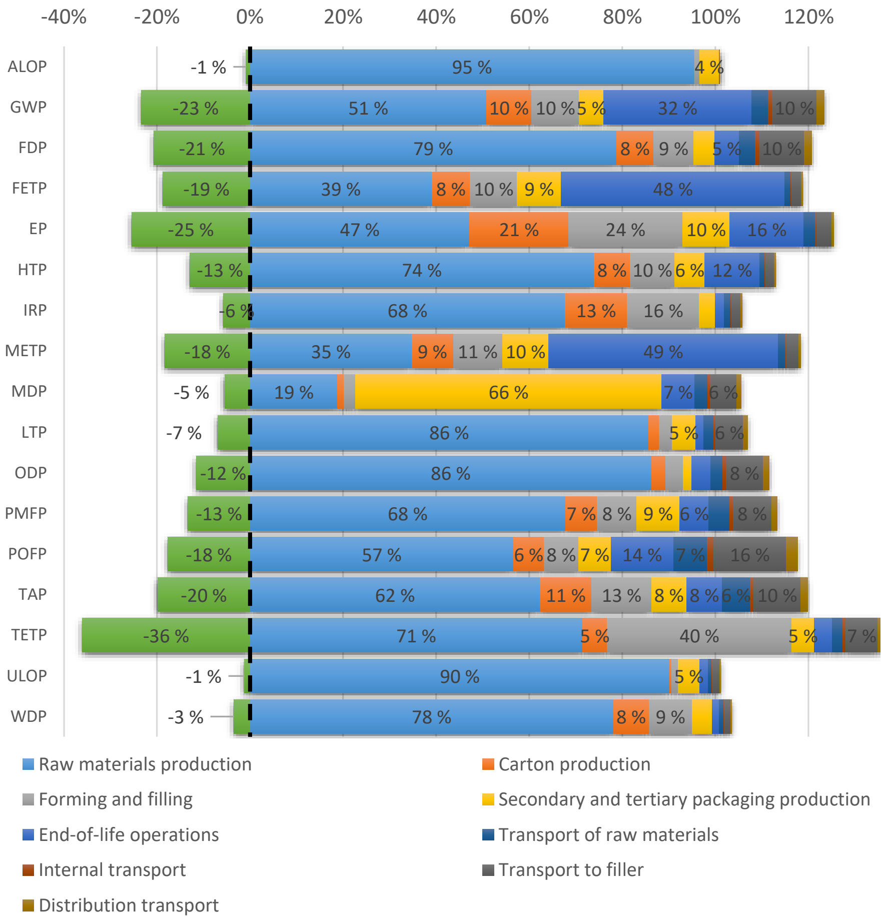

Figure 11: Relative results for generic data scenario for all impact categories[2]

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[2] ALOP: Agrucultural land occupation, GWP: Climate change, FDP: Fossil depletion, FETP: Freshwater ecotoxicity, EP: Eutrophication, HTP: Human toxicity, IRP: Ionising radiation, METP: Marine ecotoxicity, MDP: Metal depletion, LTP:Natural land traonsformation, ODP: Ozone depletion, PMFP: Particular matter formation, POFP: Photochemical oxidant formation, TAP: Terrestrial acidification, TETP: Terrestrial ecotoxicity, ULOP: Urban land occupation, WDP: Water depletion

Table 12: Absolute results for generic scenario

Impact Category	**Unit**	**Total**	**Impact**	**Credit**
Agricultural land occupation	m2a	**0,208**	0,210	-0,002
Climate change	g CO2 eq	**50,6**	62,4	-11,8
Fossil depletion	g oil eq	**17,5**	21,2	-3,6
Freshwater ecotoxicity	g 1,4-DB eq	**0,687**	0,816	-0,129
Eutrophication	g PO43- eq	**0,053**	0,067	-0,014
Human toxicity	g 1,4-DB eq	**31,0**	35,0	-4,0
Ionising radiation	g U235 eq	**24,2**	25,6	-1,4
Marine ecotoxicity	g 1,4-DB eq	**0,632**	0,748	-0,116
Metal depletion	g Fe eq	**3,968**	4,186	-0,218
Natural land transformation	m2	**3,01E-05**	3,22E-05	-2,08E-06
Ozone depletion	g CFC-11 eq	**9,59E-06**	1,07E-05	-1,11E-06
Particulate matter formation	g PM10 eq	**0,082**	0,093	-0,011
Photochemical oxidant formation	g NMVOC	**0,148**	0,174	-0,026
Terrestrial acidification	g SO2 eq	**0,156**	0,187	-0,031
Terrestrial ecotoxicity	g 1,4-DB eq	**0,012**	0,016	-0,004
Urban land occupation	m2a	**3,68E-03**	3,72E-03	-4,30E-05
Water depletion	m3	**0,427**	0,442	-0,015

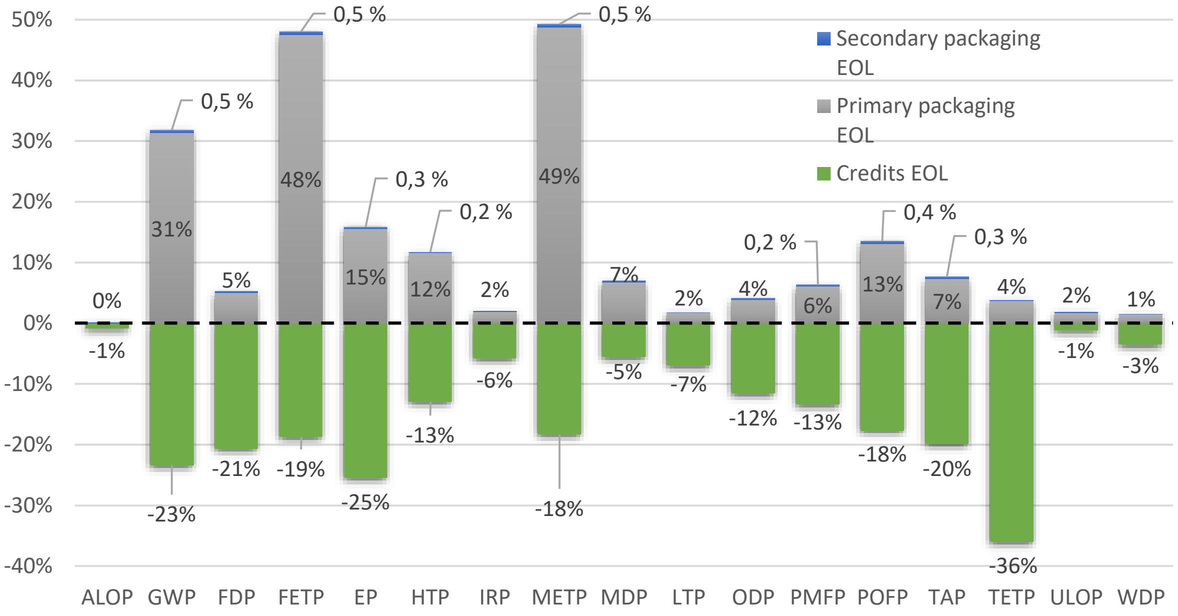

Figure 12: Comparison of waste management impacts and attributed credits in generic scenario

5.2.1 Description of results

By inspecting Figure 11 one can observe that raw materials extraction and production has a dominating impact on the majority of the impact categories. This is true for 14 out of 17 impact categories. The average relative impact is 65% to all categories.

- In freshwater- and marine ecotoxicity the impact from waste management is higher than raw materials production. Impacts for waste management stems from pollution related to disposal of various materials to landfill.
- Metal depletion is mainly caused by the production of secondary ant tertiary packaging. The source of this impact is the steel which is used in the manufacturing of the roll container.
- In terrestrial exotoxicity, there is a significant impact from forming and filling by 40%. This impact is caused by chemicals used in the process and electricity consumption.

In figure 12, a comparison is illustrated of the impact from waste management and the credits attributed to the system. For 11 out of 17 impact categories, the credits outweigh the impacts. In the case of climate change, freshwater ecotoxicity and marine ecotoxicity, the impact is significantly higher than the credit, which was pointed out for figure 11. The applied methodology described in Section 3.3.6 is a key driver of impacts versus credits. Therefore it is further tested in a sensitivity analysis in Section 5.5. As commented for the base scenario, recycling of paperboard from primary packaging is the driver for credits.

5.3 Comparison of scenarios

In this section, a comparison of the two presented scenarios will be performed to point out key differences. The focus will be on the two life cycle phases where different data has been utilised, liquid paperboard production and carton production. A comparison is possible only for the four impact indicators presented in the base scenario. Results of the comparison are illustrated below in Figure 11.

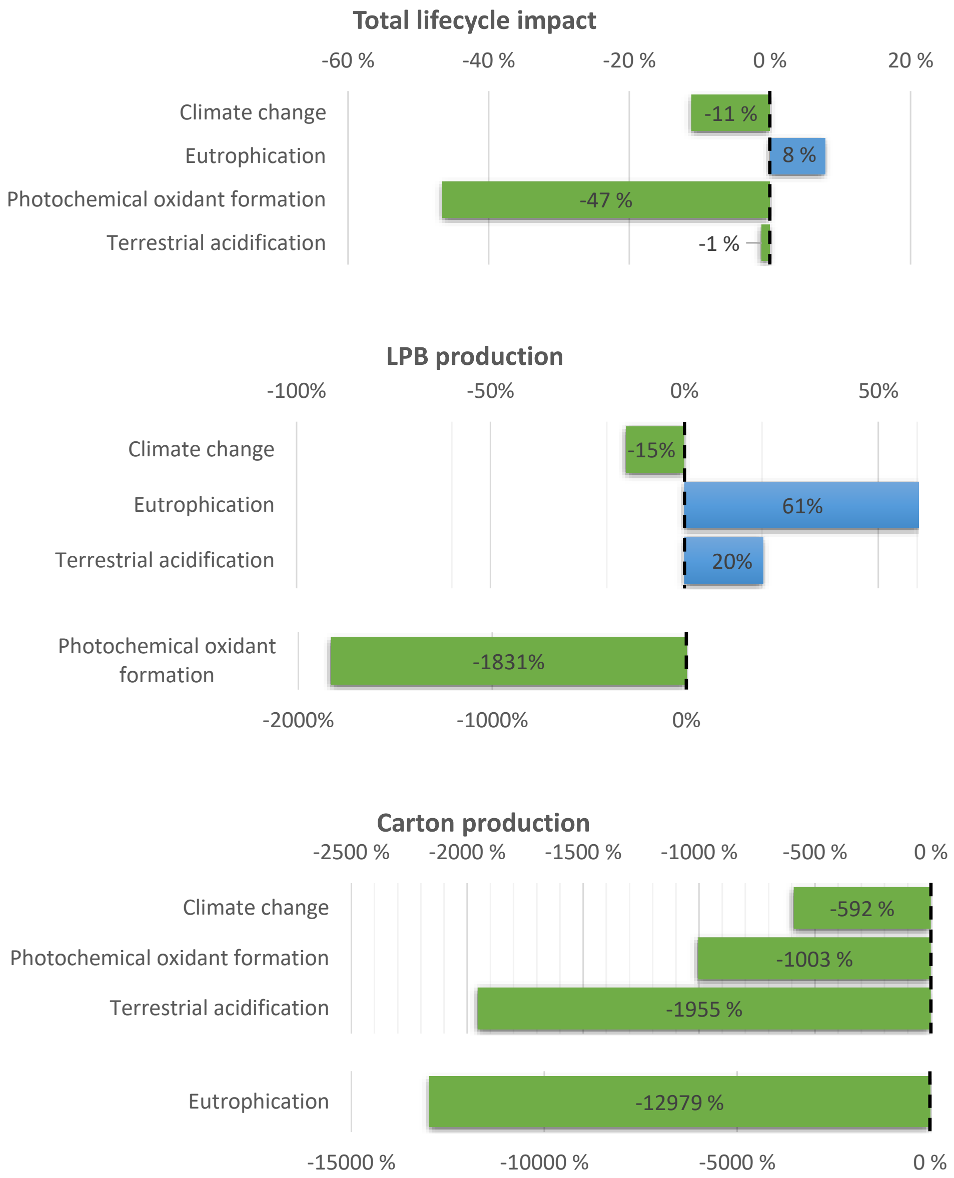

Figure 11: Comparison of impacts for the total lifecycle, production of liquid packaging board and carton production. Green color indicating lower impact in base scenario. Blue color indicating a higher impact in base scenario.

Table 13: Comparison of scenario impacts for carton- and LPB production.

		Base scenario			Generic scenario		
Impact Category	**Unit**	**LPB**	**Carton production**	**Sum**	**LPB**	**Carton production**	**Sum**
Climate change	g CO2 eq	9,4	0,7	*10,1*	10,8	4,9	*15,6*
Eutrophication	mg PO43- eq	25,4	0,1	*25,5*	9,9	11,4	*21,3*
Photochemical oxidant formation	mg NMVOC	3,3	0,9	*4,1*	62,9	9,6	*72,5*
Terrestrial acidification	mg SO2 eq	72,4	0,8	*73,3*	57,7	17,4	*75,1*

5.3.1 Total scenario impacts

Figure 11 show that impacts for the base scenario are lower for climate change, photochemical oxidant formation and terrestrial acidification, but the eutrophication potential and terrestrial acidification is higher. For climate change, the difference is 11% of the total lifecycle impact. The impact on photochemical oxidant formation is significantly lower for the base scenario by 47%, and a marginal difference of 1% is reported for terrestrial acidification. Specific impact characteristics will be further discussed below.

5.3.2 Liquid paperboard production

In this scenario, the weighted average of EPDs for two Scandinavian LPB producers is tested against average European production of LPB. The results in figure 11 show that the impact is lower for climate change and photochemical oxidant formation in the base scenario. The eutrophication potential and terrestrial acidification potential is higher. The comparison shows a significant difference, and for photochemical oxidant formation, the impact is as much as 18 times lower in the base scenario. For the generic scenario, the impact of climate change and eutrophication is mainly caused by the energy mix used in the production of the paperboard, which contains fossil fuels. For photochemical oxidant formation, the main driver is the operation of diesel lorries in transportation, and the burning of wood as a process in production. For terrestrial acidification, transportation and sulphur dioxide utilised in production is the main drivers for the impact. The results do not provide a concrete answer to which processes that cause the difference between the two scenarios because of the missing background process data for LPB production in the base scenario. The large differences between the results are discussed in section 6.

5.3.3 Carton production

By looking at figure 11 it is possible to see that the base scenario is superior in all four categories by a significantly lower impact. The higher impact in the generic scenario is caused by the electricity mix. European average electricity mix has a much greater impact than electricity from Norwegian hydropower, which is utilised in Elopak carton production through GOs. The results show a magnitude of difference reaching from 6 to as much as 130 times lower impact in the base scenario. The large differences are discussed in Section 6.

5.4 Contribution analysis

A contribution analysis has been performed on the generic scenario system to recognise the relative magnitude of impacts from background processes. Table 15 show each selected impact indicator and which background processes that contribute the most within that category. The selection of indicators is explained in Section 3.3.9.

Table 14: Most contributing processes in the generic scenario to each impact category.

	Relative contribution
Agricultural land occupation	
Forestry	97 %
Climate change	
Landfill, primary packaging board	14 %
LDPE production	12 %
Fossil depletion	
PE production, coating	29 %
PE production, closure	25 %
Freshwater ecotoxicity	
Landfill, wood ash from LPB production	16 %
Landfill, PE	16 %
Eutrophication	
Landfill, primary packaging board	10 %
Electricity, forming and filling	7 %
Human toxicity	
Landfill, wood ash from LPB production	39 %
LPB production	19 %
Ozone depletion	
PE production, coating	27 %
Solvents, injection moulding of closure	14 %
Particulate matter formation	
PE production, coating	17 %
LPB production	9 %
Photochemical oxidant formation	
LPB production	14 %
Transport of blanks to filler, lorry	6 %
Terrestrial acidification	
LPB production	11 %
PE production, coating	9 %
Water depletion	
LPB production, electricity from hydropower	99 %

5.5 Sensitivity analysis

A sensitivity analysis has been performed to test the effects on the system due to changes in certain parameters. This analysis will test the effects by changing some of the assumptions which have been made, and the methodological approach for waste management impacts. Three scenarios are considered:

- **Allocation of waste management: Cut-off approach**
- **Distribution distance**
- **Roll container: Indefinite reuse**

Figure 12 presents the effects on the entire system for the climate change indicator, for each scenario. By considering the cut-off scenario, effects are significant. The impact is 11% higher compared to the base scenario. For the two other scenarios, the effect is less significant. The change in distribution distance causes a 3% higher impact, and a 5% lower impact by changing waste management settings for the roll container. Each scenario is further described below.

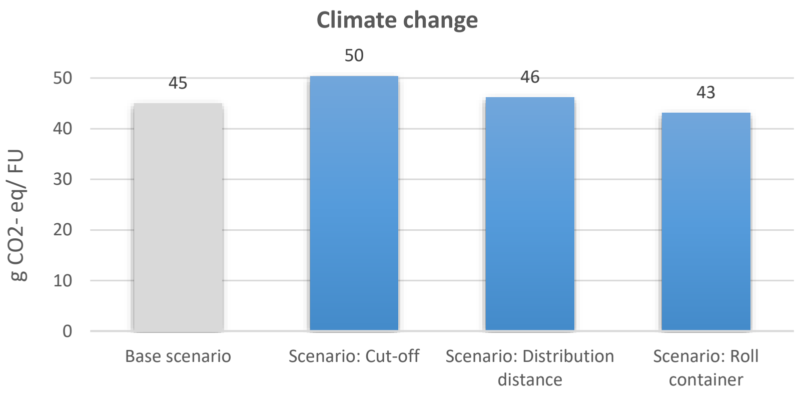

Figure 12: Comparison of climate change impacts for base scenario and scenarios created for sensitivity analysis.

5.5.1 Allocation waste management: Cut-off approach

A detailed description of the approach for waste management impacts and given credits to the base scenario are described in Section 3.3.6. In this scenario, a cut-off approach has been applied. The cut-off approach attributes all impacts to the recovered product, material or energy, in recovery processes. This means that for recycling and waste incineration, only impacts related to the collection of waste is attributed to this system. Potential credits from recovered products have been neglected. When considering waste going to landfill, impact related to the landfill process are included, but credits for recovered energy from landfill gas are not.

From Figure 13 one can see that effects are significant for all considered impact categories. The main cause for the increased impact of climate change is sourced back to impacts from the share of primary packaging which goes to landfill. Additionally, credits which were given to the base scenario for the production of recycled paperboard is now extracted and therefore causing an increased impact. The two mentioned reasons are also the case for eutrophication. The excluded credits from the production of recycled cardboard are causing the increased impacts of photochemical oxidant formation and terrestrial acidification.

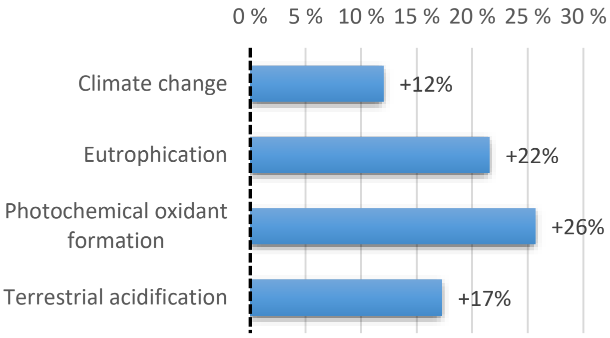

Figure 13: Imapcts for cut-off scenario.

5.5.2 Distribution distance

Distribution transport includes the finished beverage product loaded into roll containers and transported by lorry to a regional distribution centre. Applied transport distance for distribution in the base scenario was assumed to be 160 km, as described in Section 4.4.9. In this scenario, the assumed distance has been raised to 400 km, which is the same distance assumed for other transport steps in this study.

The change in results is most significant for photochemical oxidant formation, by a 7% increase. The other impact indicators are not affected significantly. As impacts from this stage were not considerable in the analysis of the base scenario, effects from changes would be expected to be small.

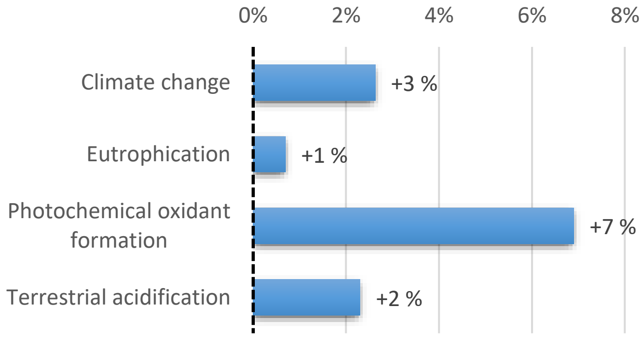

Figure 14: Impacts for distribution distance scenario.

5.5.3 Roll container: Indefinite reuse

In this scenario, the end-of-life settings for the roll container is tested. In the base scenario, the roll container is assumed to be reused 500 times before disposal. For this scenario, the roll cage container is assumed to be reused indefinitely, which implies that all activities related to production and waste management of the container are removed. Its weight in relation to transport is still accounted for.

Results in figure 15 show that impacts are slightly lower compared to the base scenario, by 4- to 7%. Event though the roll container was assumed to be reused 500 times and holds 160 cartons, which implies that $\frac{1}{500\times160}$ part of the roll container is allocated to the functional unit, the assumptions in this scenario still show a small effect on the overall environmental performance. The reason for this is the high energy intensity of the steel production process.

In the base scenario, the roll container is assumed to be disposed of in an inert landfill after its ended use. A change of assumption to recycling of the roll container, which is a more reasonable setting, would probably have affected the result of the sensitivity analysis. This is further discussed in Section 6.

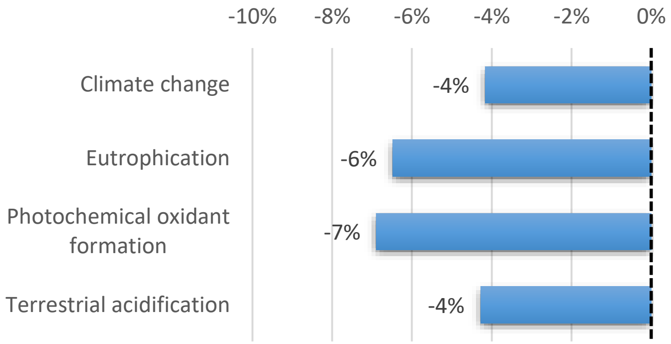

Figure 15: Impacts for roll container scenario.

6 Discussion

In this section, main findings of the study are presented. The discussion will focus on the base scenario, but significant findings in the comparison of scenarios will also be pointed out to provide a thorough understanding of the presented results. Each research questions stated in Section 1.2 will be answered and discussed separately. Also, strengths and weaknesses of results are pointed out, and general improvements to the product system will be proposed.

6.1 Main findings

1. By considering the entire lifecycle, what is the environmental impact of an average Elopak 1 litre carton for fresh milk in a European context?

The overall life cycle impact for the beverage carton in the base scenario is 45 g CO_2 -eq for climate change, 57,7 mg PO_4^3- -eq for eutrophication, 79,1 mg NMVOC for photochemical oxidant formation and 154,6 mg SO_2 -eq for terrestrial acidification. All results are given per functional unit.

A generic data scenario was created to test primary data and to provide results for all impact categories. Since data that were utilised for production of liquid packaging board in the generic scenario were older, one could expect a higher impact, because of industry technology development and improvement in assessment methods. This was not the case in all categories, and the higher impact for eutrophication contributed to an 8% higher impact to the overall life cycle. In this study, it is only possible to connect impacts to specific processes in the generic scenario. The main contributors to a high impact for photochemical oxidant formation are sourced back to forestry activities and transportation. Critical factors for the lower impact in the base scenario to this category is difficult to provide. Difference in electricity mix for carton production provided a substantially lower impact for the base scenario. This was as expected since Norwegian hydropower is much more environmental friendly than the European electricity mix which contains fossil fuels.

A sensitivity analysis was performed to test the effects of changing some of the assumption made in the system. Results show that the methodological approach for allocating impacts and credits for waste management has a critical effect on the system. The cut-off approach showed a substantial increase in impact for all categories by 12% for climate change, and up to a 26% increase in photochemical oxidant formation. By changing the distribution transport distance from 160 km to 400 km, only smaller effects were observed, which implies that the assumed distance does not cause a considerable uncertainty to the system. Regarding the scenario which tested the assumption of reusing the roll container, effects from 4% to a 7% lower impact were observed when assuming indefinite reuse. The reason for the lower impacts is that production and waste management activities are excluded from the system. A weakness of the original assumption for the treatment of the roll container after ended use has an adverse effect on this test. The roll container was originally assumed to be sent to landfill. If the assumption had been changed to recycling, which is a more reasonable approach, credits from the recovery of materials could have provided the original system a lower impact and the comparison to the sensitivity analysis would have provided a different result. By assuming, there would have been close to equal results between the base scenario and the result from the sensitivity analysis. This show that the assumption of sending the roll container to landfill is unfair to the system regarding environmental performance.

2. Which processes in the beverage carton life cycle contributes the most to the environmental impact, and what are critical variables?

The main contributor to the environmental impact is the production of raw materials. The most considerable impact comes from the production of liquid packaging board and plastics production. Liquid packaging board is by weight the main material utilised in the beverage carton. A considerable impact is observed from the production of PE resins for coating and closure. Plastic fractions in the beverage carton represent only 20 % of its total weight but still contributes 45 % to the climate change impact. A high impact is also observed in photochemical oxidant formation where plastic production represents 47%. This show that there is a much greater impact per weight from plastic resin production compared to LPB production.

Waste management does also have a considerable impact on climate change and photochemical oxidant formation. The most critical variable for this impact is first, and foremost primary packaging sent to landfill. The impact from incineration of plastic fractions in primary packaging has a considerable impact on climate change, and transport of waste is an important variable for photochemical oxidant formation. Transport to filling also contributes significantly to the latter.

It is also worth mentioning the impact to eutrophication caused by the forming and filling phase. It is measured to contribute 23% of the total and is caused by disposal of lignite spoils in the production of the European electricity mix. Transport to filling shows a relatively high impact, especially to photochemical oxidant formation. As important variables for this stage is based on assumptions, the impact will be discussed in Section 6.3.

3. What strategies would be appropriate to improve the product system environmental performance?

The analysis of this system shows that raw materials production is the most important process relating environmental impacts. Critical processes prove to be the production of liquid packaging board and plastic resins in primary packaging. Strategies for improvement would be to work in close contact with suppliers in order to share experience and to move towards common goals which can create development for all parties and to ensure that the environment is among top priorities. Relating plastic production, renewable plastics is a future pathway for packaging products and has already been taken into production. Strategies are further discussed in Section 6.4.

6.2 Agreement with literature

By comparing results from the base scenario to the presented literature in figure 2, impacts to climate change proves to be lower than for all of the presented core studies. This is also the case in 4 out of 5 presented additional studies. The only study showing a lower impact on climate change is the EPD of an Elopak PE coated beverage carton in a cradle-to-gate perspective. For eutrophication, the performance is significantly worse compared to core studies. Only in the BIO study, which represents a wine carton with an aluminium layer, the impact is higher. The results of this study show a more than 50% higher impact to eutrophication compared to the impact presented in the literature. By looking back at the comparison for scenarios, the base scenario showed a 60% higher impact to eutrophication in LPB production. In addition, raw materials were the main contributor and the production of LPB had a 62% impact among the other raw materials. This proves that the higher impact is mainly caused by LPB production, but the exact reason can not be pointed out as background data are missing. For photochemical oxidant formation[3], the comparison show that the impact in the base scenario is higher than for the BIO and IVL study by as much as 112%. It is hard to point out critical variables for this poor performance, but the largest impact comes from LPB production and transportation to the filling facility. The acidification potential shows a significantly lower impact compared to the literature and is 33% lower in this study.

As described above the results vary substantially both among the presented literature and compared to this study. The variations can be linked to limitations and uncertainties such as excluded processes, variations of system boundaries and general assumptions. This makes it difficult to compare results from LCA studies.

6.3 Strengths and weaknesses of results

Some of the most important factors about providing results of high quality in LCA modelling lies within the creation of clear goals, defining system boundaries and the collection of data. As this study was encouraged by Elopak, main goals and boundaries were already set from an early stage relating the geographical scope, time frame for primary data and its most important objectives. Even though the analysis had to be narrowed down to only consider one product, this did not affect the final result since there were many similarities between the two original systems. The main strengths of this study are the quality of the provided data from Elopak. An extensive database were provided for most

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[3] To compare, the results in figure 2 has to be divided by a factor of 0,592 (Goedkoop et al., 2009) to obtain equal units used in this study

processes regarding Elopak activities in addition to data for production of essential raw materials. NTNU provided access to software for impact assessment and the Ecoinvent 2.2 database. In addition, this study was supervised by experienced researchers at NTNU which provided guidance along the entire project work.

To provide updated and most realistic results, datasets has been updated by using literature, and calculated results for cradle-to-gate impacts have been compared and checked with the Elopak internal database. A second scenario was also created to close data gaps and to test the applied primary data against generic databases. The applied methodology has utilized a specific framework for LCA for carton beverage packaging, a PCR (ACE, 2015), which follow the ISO standard for life cycle assessment(Finkbeiner et al., 2006).

Some simplifications have been made to the methodology in the PCR regarding given end-of-life credits, where settings have been assumed to be similar for both primary, and secondary and tertiary packaging in this study. The assumption leads to a lower impact due to the given credits for recovery of materials and energy from waste treatment processes of secondary and tertiary packaging. Some assumptions have also been made regarding transport distances, distribution packaging type and end-of-life treatment. The transport distances which were not documented in the primary data have been based on the PCR. Transportation data reported in the PCR are based on statistical average data in a European context from the ACE, and should thereby represent this systems settings and not cause significant uncertainties. The assumption for the use roll containers as distribution packaging is based on data from WRAP (2010), a study of milk packaging in the UK. Roll containers are also used in distribution in Norway. The assumption regarding the waste treatment for materials in the roll container are discussed above in section .

Loss of packaging during processes has only been accounted for in the forming and filling phase. For other primary data, no loss has been accounted for due to lack of data. As this report not have been reviewed and checked by professional researchers within the field of study, there are uncertainties regarding possible calculation errors and methodology deviations which could affect the results. Another factor which is both a strength and weakness is the use of EPDs as data input. The EPDs provide up to date and case-specific data but provide a lack transparency to the results which make it difficult to pinpoint important processes that contribute to the impacts.

6.4 Implication of findings and further research

Results from this study show that Elopak carton packaging for fresh milk performs well for certain impact categories. The most important parameters show that there are potential improvements in the packaging system, especially related to raw materials production. Some parameters have already been substantially improved compared to previous unpublished background studies for Elopak products. Carton specifications, such as type and weight of materials are key drivers for impacts, and the effort to reduce weight and to utilise materials which are environmentally friendly will be necessary to reduce life cycle impacts even further. This does not only apply to this system but for carton packaging in general. As shown, plastics in primary packaging have a considerable impact per produced carton, and improvements to this parameter would cause improvements of the carton environmental performance. Utilisation of renewable plastics has already been taken into the production of beverage cartons (ELOPAK, 2014). Processes within the LPB production are important. Possible improvements would be to ensure environmental friendly forestry and transport, to use renewable energy sources in production and to reduce the amount of chemicals in process. Diesel powered machinery and trucks may be replaced by battery powered engines utilising renewable energy sources. Also, it will be important to enhance waste management activities. An increase in the share of packaging sent to recycling will save production of virgin materials and lower environmental impacts. Energy recovery in waste incineration and from recovered landfill gas should also be encouraged.

Use of the results presented in this report for comparison purposes does only apply to similar product systems, where critical parameters such as functional unit, system boundaries and others are similar. Parameters which are unique to this product system can be critical for environmental performance, and use of results should be carried out with caution.

The goal of this study was to provide new information about the environmental performance of carton packaging at Elopak and to help guide future work in a direction towards an, even more, environmental friendly packaging sector. The many strengths of this study hope to prove that results are of high quality even though the work has not been accomplished by experienced researchers within the field of study.

7 Conclusion

As discuessed in previous chapter, the environmental impact is 45 g CO_2 -eq for climate change, 57,7 mg PO_4^3- -eq for eutrophication, 79,1 mg NMVOC for photochemical oxidant formation and 154,6 mg SO_2 -eq for terrestrial acidification. All results are given per functional unit.

The most important processes regarding environmental impact proves to be the production of raw materials, where liquid packaging board and plastic resins utilized in primary packaging are critical variables. The production of liquid packaging board has the highest impact to eutrophication and terrestrial acidification. Plastics production show a higher impact to climate change, and because of the intesitivity of the impact per weight of plastics it would provide the system strong benefits by reducing the amount of plastics. Waste management activities also show a significant impact to climate change and photochemical oxidant formation.

Strategies to improve the system environmental performance will be to assess the most important parameters mentioned above and to work in close contact with raw materials suppliers to ensure more environmental friendly materials. The type of materials and the product weight are important factors which have a substantial effect. Utilization of renewable plastics has already been taken into production of cartons and will potentially provide a lower environmental impact. Utilisation of renewable energy in the LPB production and forestry activities are important factors to lower the impact. It will also be important to promote recycling of all materials to avoid production of virgin materials. In addition, utilization of recovered energy in waste incineation and from collected landfill gas should be further improved. Waste management improvements can be one of the most important steps for future pacakging. Consumer waste is not directly connected to producing companies, and will require strong cooperation between politicians and industries.

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Appendix A: Environmental impact indicators

Global warming potential

The impact of anthropogenic emissions such as CO_2, CH_4, and N_2O where the impact is related to the absorption of heat radiation inside the atmosphere. This phenomenon is referred to as radiative forcing and has various effects on climate and ecosystems. The most discussed themes are temperature changes and sea level rise. The indicator is expressed in kilograms CO_2 equivalents and is calculated by summing up the global warming potential of all substances based on the impact over a given time horizon. The most commonly used time horizon is 100 years (Amienyo, 2012).

$$GWP = \sum_{j=1}^{J} GWP_j B_j \tag{1}$$

GWP_j is the global warming potential of substance j and B_j is the quantity of the substance.

Acidification potential

Acidifying pollutants such as SO_2, NOx, and NHx affect soil, biological organisms, ecosystems and groundwater (Amienyo, 2012). As an example, ocean acidification leads to a reduction of calcification which affects corals which can cause a chain reduction affecting the entire food web of the oceans (Verones, 2016). The acidification potential is measured in kilograms of SO_2 equivalents and is calculated with the equation:

$$AP = \sum_{j=1}^{J} AP_j B_j \tag{2}$$

AP_j is the acidification potential of substance j, and B_j is the quantity of the substance.

Eutrophication potential

Eutrophication has an impact on both terrestrial and aquatic ecosystems where for example increase in biomass production, due to an increase in nutrient levels of mainly nitrogen and phosphorus, leads to lower oxygen levels in the water. This affect living organisms within the concerned waterbody. The eutrophication potential is measured in kilograms of PO_4^3- equivalents (Amienyo, 2012).

$$EP = \sum_{j=1}^{J} EP_j B_j \tag{3}$$

EP_j is the eutrophication potential of substance j, and B_j is the quantity of the substance.

Photochemical oxidant creation potential

The formation of reactive compounds such as peroxyacetyl nitrate and ozone on a near-ground level by the effect of sunlight on air pollutants. This may have a negative effect on human health, vegetation and ecosystems. The indicator is expressed in kilograms of NMVOC and quantified by the equation (Amienyo, 2012):

$$POCP = \sum_{j=1}^{J} = POCP_j B_j \tag{4}$$

Appendix B: Mathematical operations in LCA modelling

The goal in LCA modelling is to describe the total environmental load associated with a functional unit. The functional unit describes the desired output from a system, service or a product. First, it is necessary to identify the total acticity generated in all processes which is involved. Secondly, all emissions emitted per functional unit has to be added to the system. Emissions factors are then multiplied with the activity to find the emissions generated in each node as a results from the requirement of the functional unit. Total emissions for a system equals the sum of direct and indirect emissions (Strømman, 2010).

The interdependence between the processes is normally modelled as a linear system. The formulations were first developed by Wassily Leootief. The open Leontief model equates an output vector x with a intermediate demand $A * x$ plus final demand vector y.

$$x = Ax + y \tag{5}$$

A is the requirement matrix where the coeffisients a_{ij} denotes the amount required by process i per unit output of process j, as described in equation 6. The x vector describes the production output in each node, and the external demand vector y is the requirment of products that the network has to deliver, typically the functional unit.

$$a_{ij} = \frac{\text{amount of } i \text{ required}}{\text{output of } j} \tag{6}$$

Equation 5 can be rewritten by using the Leontief Inverse $L = (I - A)^{-1}$. Rearranging yields,

$$x = Ax + y \;\Leftrightarrow\; (I - A)x = y \;\Leftrightarrow\; x = (I - A)^{-1}y \tag{7}$$

Where

$$L = (I - A)^{-1} \;\Rightarrow\; x = Ly \tag{8}$$

The coeffisients in the L matrix, l_{ij} represents the amount of output of process i that is rquired per unit of final delivery of process j.

To calculate total emissions and the environmental loads assiociated with the system and a given external demand a contribution analysis is performed. The next equations will describe each step to obtain desired matrices and vectors. A definition of each vector and matrix is given in table 15(Strømman, 2010).

$$e = Sx = SLy \tag{9}$$

$$E = S\hat{x} = S\widehat{Ly} \tag{10}$$

$$d = Ce = CSx = CSLy \tag{11}$$

$$D_pro = CE = CS\hat{x} = CS\hat{L}y \tag{12}$$

$$D_str = C\hat{e} = C\hat{S}x = CS\hat{L}y \tag{13}$$

Table 15: Matrices and vectors used in a contribution analysis (Strømman, 2010).

pro		Processes
str		Stressors
imp		Impact categories
A	pro x pro	Matrix of inter process requirments
y	pro x 1	Vector of external demand of processes
x	pro x 1	Vector of outputs for a given external demand
L	pro x pro	The Leontief inverse, Matrix of outputs per unit of external demand
S	str x pro	Matrix of stressors intensities per unit of output
e	str x 1	Vector of stressors generated for a given external demand
E	imp x pro	Matrix of stressors generated from each proecss for a given external demand
C	imp x str	Characterization matrix
d	imp x 1	Vector of impacts generated for a given external demand
Dpro	imp x pro	Matrix of impacts generated from each process for a given external demand
Dstr	imp x str	Matrix of impacts generated from each stressor for a given external demand

Appendix C: Envrionmental impact results from literature

IVL

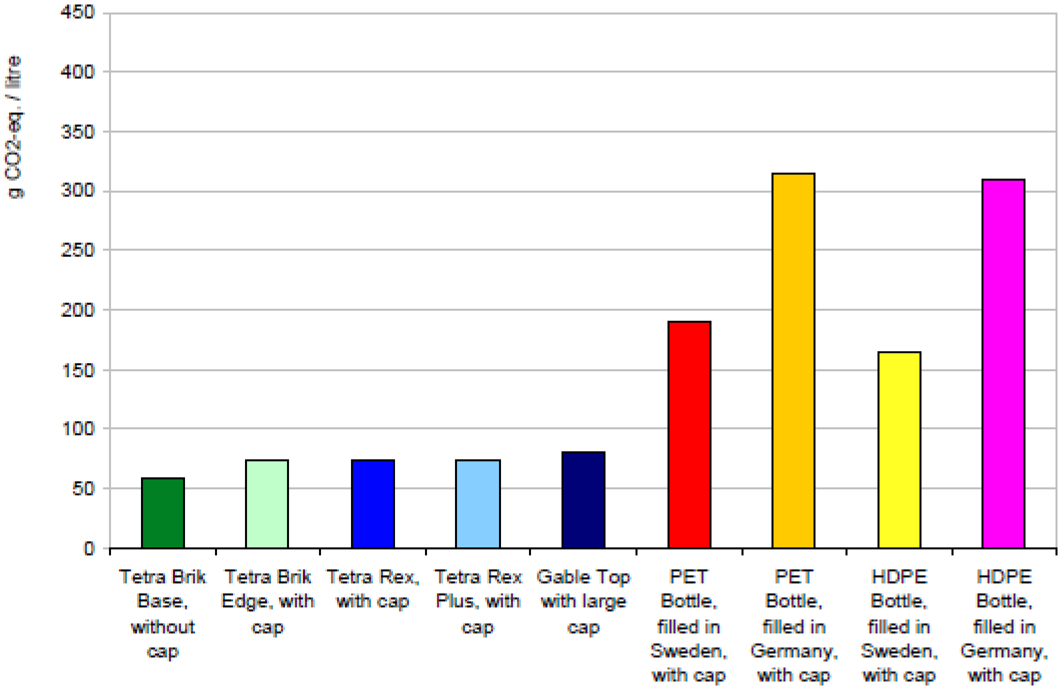
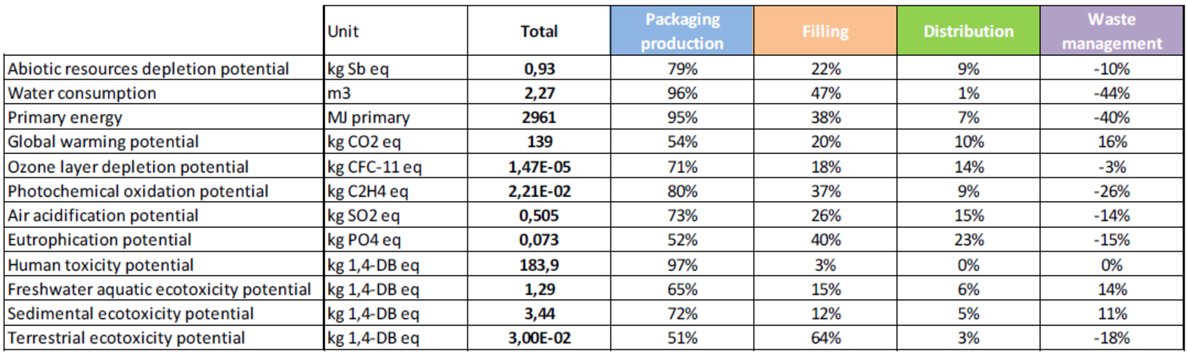


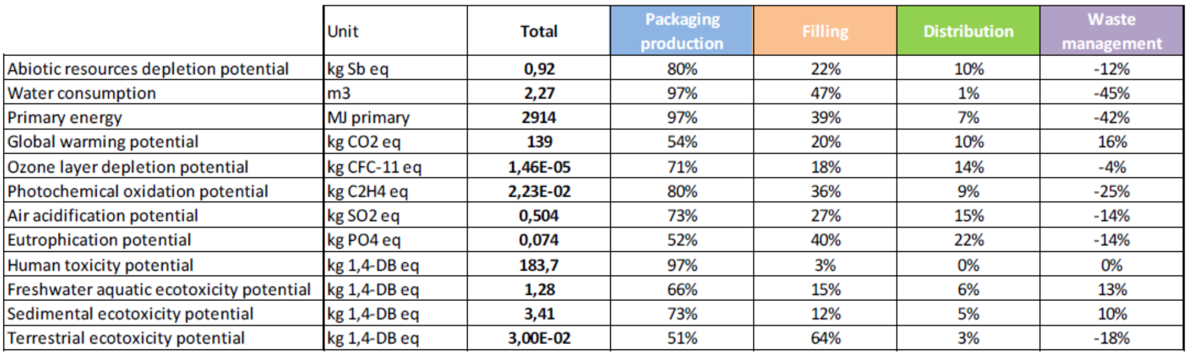
Figure 16: Impact to climate change for 1-litre dairy packaging on the Swedish market(Jelse et al., 2009).

BioIntelligence



	Unit	Total	Packaging production	Filling	Distribution	Waste management
Abiotic resources depletion potential	kg Sb eq	**0,93**	79%	22%	9%	-10%
Water consumption	m3	**2,27**	96%	47%	1%	-44%
Primary energy	MJ primary	**2961**	95%	38%	7%	-40%
Global warming potential	kg CO2 eq	**139**	54%	20%	10%	16%
Ozone layer depletion potential	kg CFC-11 eq	**1,47E-05**	71%	18%	14%	-3%
Photochemical oxidation potential	kg C2H4 eq	**2,21E-02**	80%	37%	9%	-26%
Air acidification potential	kg SO2 eq	**0,505**	73%	26%	15%	-14%
Eutrophication potential	kg PO4 eq	**0,073**	52%	40%	23%	-15%
Human toxicity potential	kg 1,4-DB eq	**183,9**	97%	3%	0%	0%
Freshwater aquatic ecotoxicity potential	kg 1,4-DB eq	**1,29**	65%	15%	6%	14%
Sedimental ecotoxicity potential	kg 1,4-DB eq	**3,44**	72%	12%	5%	11%
Terrestrial ecotoxicity potential	kg 1,4-DB eq	**3,00E-02**	51%	64%	3%	-18%

Figure 17: Breakdown of impacts of the 1-liter carton in Sweden (BIO, 2010)



	Unit	Total	Packaging production	Filling	Distribution	Waste management
Abiotic resources depletion potential	kg Sb eq	**0,92**	80%	22%	10%	-12%
Water consumption	m3	**2,27**	97%	47%	1%	-45%
Primary energy	MJ primary	**2914**	97%	39%	7%	-42%
Global warming potential	kg CO2 eq	**139**	54%	20%	10%	16%
Ozone layer depletion potential	kg CFC-11 eq	**1,46E-05**	71%	18%	14%	-4%
Photochemical oxidation potential	kg C2H4 eq	**2,23E-02**	80%	36%	9%	-25%
Air acidification potential	kg SO2 eq	**0,504**	73%	27%	15%	-14%
Eutrophication potential	kg PO4 eq	**0,074**	52%	40%	22%	-14%
Human toxicity potential	kg 1,4-DB eq	**183,7**	97%	3%	0%	0%
Freshwater aquatic ecotoxicity potential	kg 1,4-DB eq	**1,28**	66%	15%	6%	13%
Sedimental ecotoxicity potential	kg 1,4-DB eq	**3,41**	73%	12%	5%	10%
Terrestrial ecotoxicity potential	kg 1,4-DB eq	**3,00E-02**	51%	64%	3%	-18%

Figure 18: Breakdown of impacts of the 1-liter carton in Norway(BIO, 2010)

IFEU

Table 16: Environmental impact for SIG Combibloc beverage carton combiblocSlimline EcoPlus 1000mL with closure cCap. LC part A showing results for production of primary packaging to factory gate, and LC part B showing results for filling, distribution, secondary/tertiary packaging and end-of-life processes. Benefits from end-of-life processes are listed as "Credits"(IFEU, 2012)

	cb3 EcoPlus cCap				
Impact category	**LC part A**	**LC part B**	**Credits**	**Net results**	unit
Acidification	0,20	0,10	-0,04	*0,26*	kg SO2-eq
Climate change	41,39	45,20	-14,48	*72,11*	kg CO2-eq
Aquatic eutrophication	14,45	6,43	-2,29	*18,60*	g PO4-eq
Terrestrial eutrophication	18,55	12,87	-3,31	*28,11*	g PO4-eq
Summer smog	46,36	13,93	-4,49	*55,81*	g ethene-eq
Human toxocity - PM10	0,17	0,10	-0,03	*0,24*	kg PM10-eq
Human toxicity - carciogenic risk	1,79	1,09	-0,26	*2,63*	mg As-eq
Fossil resource consumption	13,60	7,89	-3,20	*18,29*	kg crude oil -eq
Use of natureforestry	82,66	13,13	-5,56	*90,23*	m2*year
Total primary energy	1,64	0,71	-0,38	*1,97*	GJ
Non- renewable PE	0,98	0,58	-0,24	*1,32*	GJ
Transport intensity	1,92	3,48	-0,13	*5,26*	km

WRAP

Table 17: Carton with screwcap. Cradle-to-grave results with different end-of-life scenarious(WRAP, 2010).

Impact category	Unit	Landfill	Energy from waste	Recycling in Sweden
Abiobatic resources depletion	kg Sb-eq	0,388	0,217	0,262
Climate change	kg CO2-eq	42,1	36,6	41,4
Photo-oxidant formation	kg C2H4 -eq	0,0313	0,0325	0,0293
Eutrophication	kg PO4 3 -eq	0,0248	0,025	0,0166
Acidification	kg SO2-eq	0,152	0,143	0,117
Human toxicity	kg 1,4-DB -eq	7,76	7,08	6,24
Aquatic freshwater ecotoxicity	kg 1,4-DB -eq	1,25	0,88	0,674

Table 18: Gable-top carton with closure system. Cradle-to-grave results for different end-of-life scenarios.

Impact category	**Unit**	**Landfill**	**Energy from waste**	**Recycling in Sweden**
Abiobatic resources depletion	kg Sb-eq	0,291	0,158	0,207
Climate change	kg CO2-eq	35,7	26,8	31,9
Photo-oxidant formation	kg C2H4 -eq	0,0314	0,033	0,0291
Eutrophication	kg PO4 3 -eq	0,0241	0,247	0,0149
Acidification	kg SO2-eq	0,132	0,128	0,096
Human toxicity	kg 1,4-DB -eq	7,38	6,91	5,9
Aquatic freshwater ecotoxicity	kg 1,4-DB -eq	1,17	0,909	0,677

Appendix D: Ecoinvent 2.2 datasets

Table 19: Ecoinvent processes which have been utilised in this study.

Ecoinvent 2.2 processes	
corrugated board base paper, wellenstoff, at plant/ RER/ kg	injection moulding/ RER/ kg
disposal, inert waste, 5% water, to inert material landfill/ CH/ kg	kraft paper, unbleached, at plant/ RER/ kg
disposal, packaging cardboard, 19.6% water, to municipal incineration/ CH/ kg	light fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ
disposal, packaging cardboard, 19.6% water, to sanitary landfill/ CH/ kg	liquid packaging board, at plant/ RER/ kg
disposal, packaging paper, 13.7% water, to municipal incineration/ CH/ kg	logs, mixed, burned in furnace 100kW/ CH/ MJ
disposal, packaging paper, 13.7% water, to sanitary landfill/ CH/ kg	natural gas, burned in industrial furnace >100kW/ RER/ MJ
disposal, polyethylene terephtalate, 0.2% water, to sanitary landfill/ CH/ kg	polyethylene, HDPE, granulate, at plant/ RER/ kg
disposal, polyethylene, 0.4% water, to municipal incineration/ CH/ kg	polyethylene, LDPE, granulate, at plant/ RER/ kg
disposal, polyethylene, 0.4% water, to sanitary landfill/ CH/ kg	refinery gas, burned in furnace/ RER/ MJ
electricity, medium voltage, production FI, at grid/ FI/ kWh	solid unbleached board, SUB, at plant/ RER/ kg
electricity, medium voltage, production RER, at grid/ RER/ kWh	steel product manufacturing, average metal working/ RER/ kg
electricity, medium voltage, production SE, at grid/ SE/ kWh	steel, converter, low-alloyed, at plant/ RER/ kg
electricity, production mix RER/ RER/ kWh	tap water, at user/ RER/ kg
ethanol, 99.7% in H2O, from biomass, production RER, at service station/ CH/ kg	toner, colour, powder, at plant/ GLO/ kg
EUR-flat pallet/ RER/ unit	transport, freight, rail/ RER/ tkm
extrusion, plastic film/ RER/ kg	transport, lorry 16-32t, EURO5/ RER/ tkm
hard coal, burned in industrial furnace 1-10MW/ RER/ MJ	transport, transoceanic freight ship/ OCE/ tkm
heat, at cogen with biogas engine, agricultural covered, allocation exergy/ CH/ MJ	waste paper, mixed, from public collection, for further treatment/ RER/ kg
heat, at flat plate collector, multiple dwelling, for hot water/ CH/ MJ	waste paper, sorted, for further treatment/ RER/ kg
heat, natural gas, at boiler modulating >100kW/ RER/ MJ	wood chips, from forest, hardwood, burned in furnace 1000kW/ CH/ MJ
hydrogen peroxide, 50% in H2O, at plant/ RER/ kg	