Environmental Impact of Packaging

Margarida Leonora Muller Valério Durão

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Supervisor(s): Dr. Ivana Dencic
Prof. Dr. Ana Maria de Figueiredo Brites Alves

Examination Committee

Chairperson: Prof. Dr. Henrique Aníbal Santos de Matos
Supervisor: Dr. Ivana Dencic
Member of the Committee: Miguel Ângelo Joaquim Rodrigues

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Corbion

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Resumo

Nos últimos anos, a evolução da indústria mundial conduziu a uma urgente mudança de paradigma com o objetivo de combater as alterações climáticas. A transição da atual economia linear para uma economia circular é essencial para reduzir as emissões de gases de efeito de estufa.

Esta dissertação foca-se no estudo de embalagens, uma das áreas que as indústrias mais têm investido para o desenvolvimento sustentável com vista a facilitar a implementação do modelo de economia circular. Este estudo tem como objetivo entender a situação relativa à utilização de embalagens pela Corbion, com foco nas principais tendências, preocupações e requisitos das várias regiões. Além disso, um dos objetivos é determinar o impacto ambiental de vários tipos de embalagens a partir de um estudo desde o "berço até à cova" e recorrendo à metodologia de Avaliação de Ciclo de Vida (ACV) através do uso do software SimaPro. Os resultados são apresentados através de um conjunto de categorias de impacto: Potencial de Aquecimento Global, Uso de Energia Renováveis, Uso de Energias Não-Renováveis, Uso de Terreno e Uso de Água.

Os resultados demonstram que a produção do material é o passo do ciclo de vida que apresenta a maior contribuição para o impacto ambiental nas várias categorias de impacto, enquanto que o transporte é o passo que menos contribui. Devido ao impacto reduzido causado pela produção de papel, os resultados evidenciam que as embalagens de papel apresentam uma melhor performance ambiental do que a maioria das opções de plástico. Além disso, a substituição de embalagens maiores por embalagens de menor capacidade contribui para a diminuição das emissões de Gases de Efeito de Estufa.

Foram, ainda, analisados vários cenários para estudar a viabilidade das alterações sugeridas em algumas das embalagens. Estas sugestões incluem a utilização de materiais reciclados e bioplásticos, a redução da quantidade de materiais ou ainda, a possibilidade de reutilização e de recondicionamento. Com base numa das mais atuais tendências em embalagens, redução de material, os resultados mostram que diminuir a quantidade de plástico utilizada irá diminuir emissões. Dependendo da embalagem analisada, concluiu-se que diminuição do impacto no Potencial de Aquecimento Global pode chegar a 41% ao utilizar HDPE reciclado, 32% através da reutilização de paletes ou 44% ao utilizar aço 100% reciclado. Além destes cenários, foram estudados outras possibilidades.

Desta forma, concluiu-se que existe potencial para melhorar a performance ambiental das embalagens em estudo.

Palavras – Chave

Embalagens. ACV. Impacto Ambiental.

Abstract

In recent years, the evolution of the global industry has led to an urgent call to change the economy's paradigm to fight climate change. A shift from the current "take-make-dispose" approach to a circular economy is needed in order to reduce emissions of greenhouse gases.

In this work the focus is on packaging which is one of the several areas that industries have been investigating regarding sustainable development aiming the implementation of the circular economy model. The current situation of packaging used by Corbion has been assessed highlighting emerging trends, main concerns, and requirements across different geographies. The evaluation of the environmental impact of packaging alternatives is made by using a Life Cycle Assessment (LCA) methodology through a cradle-to-grave approach. The results are classified per region and are expressed through a set of impact categories: Global Warming Potential, Nonrenewable Energy Use, Renewable Energy use, Land Use and Water use.

Material production has proven to be the life cycle stage that has the highest impact in the analysed categories while transport is the stage with smallest contribution. Due to the low impact of the production of paper, results evidence that all paper options perform better than most plastic options. The shift between smaller packaging into larger options should be carried out whenever possible as it often contributes to the decrease of GHG emissions.

Moreover, several scenarios are analysed to study the viability of improvements on the impact of packaging. These improvement scenarios include the use of recycled and biobased materials, the reduction of material content or the possibility of reuse and reconditioning of packaging. Following one of the major trends in packaging regarding material reduction, results show that decreasing plastic content, either by decreasing wall thickness of drums or by removing inner plastic lining, translates into savings. Depending on packaging option, it was seen that savings in GWP can reach up to 41% by switching into recycled HDPE plastic, 32% by reusing pallets or 44% of saving when using 100% recycled steel. Other different scenarios were also analyzed.

Results demonstrate the existence of potential for improvement of the environmental performance of packaging.

Key-Words

Packaging. LCA. Environmental Impact. Cradle-to-grave.

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Nomenclature

APOS	Allocation at the Point of Substitution
BR	Brazil
CED	Cumulative Energy Demand
CFC	Chlorofluorocarbons
CH	Switzerland
CH_4	Methane
CO_2	Carbon Dioxide
EHS	Environment, Health and Safety
eq	Equivalent
ES	Spain
EUR	Europe
FDA	Food and Drug Administration
FIBC	Flexible Industrial Bulk Container
FU	Functional Unit
GHG	Greenhouse Gases
GLO	Global
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HDPE	High-Density Polyethylene
IBC	Industrial Bulk Container
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
Kg CO_2 Eq	Kilograms of Carbon Dioxide Equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low-Density Polyethylene
N_2O	Nitrous Oxide
NL	Netherlands
NREU	Nonrenewable Energy Use
PCR	Post-Consumer Resin
PE	Polyethylene
PEF	Product Environmental Footprint
PLA	Polylactic Acid
RER	Europe
REU	Renewable Energy Use
RoW	Rest of the World
TH	Thailand
U	Unit Process
US	United States of America
USA	United States of America

CHAPTER 1

Introduction

Over the past years, there has been an increasing pressure in the economy caused by population growth and increasing urbanization. The global population is expected to reach 9 billion people in 2050 and 11.2 billion by 2100 [1]. The United Nations estimates that by 2050, 68% of the world population will live in urban areas [2]. This level of urbanization combined with the current patterns of consumption put a heavy pressure on the economy that needs to be able to attend to consumer demand and develop a system of distribution that ensures a fast, safe and effective delivery of goods. Due to this economic development and fast industrial pressure, many industries, packaging included, felt the need of accelerating its growth to meet demand. This pressure on the industry was inevitably accompanied by several environmental harmful issues such as air, water and soil pollution, acidification of ecosystems and climate change.

In recent years, environmental concerns related to packaging, with great emphasis on plastics, became relevant. Although plastic is not the only material that constitutes packaging, there is no doubt that it is one of the most used due to its price, weight and ease of use. Between 1950 and 2018 plastic production globally grew from 1.5 million metric tonnes to 359 metric tonnes per year and it keeps increasing at high rates [3]. This huge growth of plastic production and consumption is deeply worrying as most of it ends up in streams, rivers, and ultimately in oceans. Rethinking all the plastic packaging production and supply chain is thus mandatory. Regarding plastic disposal it was published that “91% of all plastic ever made isn’t recycled” and “only 12% has been incinerated” [4].

Globally speaking, the origin of these damages inflicted on the environment is the “take-make-dispose” model of consumption which is the basis of the linear economy concept. According to this model, the standard procedure of the industry is to extract resources from nature and use energy to convert them into certain goods which are then sold to an end consumer. After their usage, most of these products are discarded when they no longer satisfy its purpose. To support this procedure, 65 billion tonnes of raw material entered the economic system in 2010 and this number will continuously grow reaching 82 billion tonnes in 2020 [5]. Significant material resources are thus being explored at an irresponsible rate creating short-term prosperity.

As a result, the global issues of climate change and earth´s temperature never been so pressing. Continuing to conduct business within this pattern would mean that all that raw material would become waste, failing to capture possible value. The recognition that human action greatly influences these changes puts most industries under tight scrutiny, pushing them to engage in global solutions that aim for carbon neutrality. It is an absolute priority to come up with sustainable alternatives.

The circular economy concept, which simplified model is represented in Figure 1, appears as a possible solution for the existing linear economy. It is a concept that intends to reduce environmental pressures linked to resource extraction, emission, and waste. The circular economy aims to rethink the way consumption of finite resources is being explored as well as eliminate waste out of the system. Thus, it focuses in keeping material resources within the system and use them to the maximum extent while maintaining economic prosperity [6]. Although some scholars still look at this concept with some reluctance, calling it a “theoretical dream” [7], the transition towards circular economy is accepted and has become one of the main priorities in the industry.

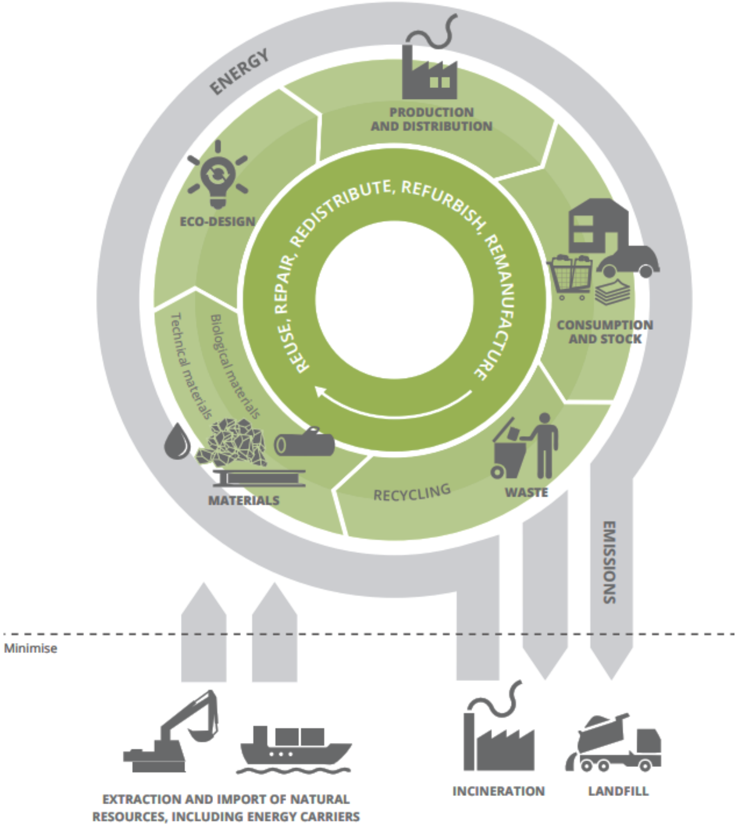

Figure 1 - Circular Economy Simplified Model (Source : *[8]*)

The inner circle of the cycle represented in Figure 1, demonstrates actions that need to be carried out in order to minimize resource input and waste generation such as reuse, repair, redistribution, refurbishment and remanufacture.

The middle cycle represents the material flows and all the steps that make up the life cycle of a certain material or product. These steps are material extraction, eco-design, production and distribution, consumption, and waste management. The material extraction step involves two types of materials: “biological, that can return to the biosphere as feedstock and technical which cannot biodegrade nor enter the biosphere” [9]. It is essential that these types of materials are kept at their highest utility and value throughout the cycles. Eco-design is a key factor in circular economy, and it focuses on modifying the product to facilitate reuse, remanufacturing and closing the loop in general. Production step directly aims to minimize material input and limiting outputs of non-recyclables and hazardous waste. Consumption is influenced by citizens, governments, and business behavior as well as patterns of use. As it is presented in this cycle, recycling is the preferred end of life option to guarantee that resources are kept within the system. It is essential to feed materials back into the economy and avoid sending waste to landfill or to incineration. One of the benefits of this approach is that the dependency on extraction and import of natural resources decreases and consequently emissions to the environment will also decrease.

The outer circle represents energy flows in this model. Both energy efficiency and usage of renewable energy should increase. While many companies are still seeking to understand the benefits of the transition from linear to circular economy, fortunately, a significant number of other companies are already seriously planning to make the shift. These companies understood the great benefit of keeping products and materials in use for longer periods of time as this mean less resource extraction, less risk in supply chains and less environmental impact. They recognize the need of a more sustainable business activity and are including sustainability in their actual decision-making strategy. However, the transition from linear to circular economy is not simple. In a first approach, companies must evaluate and seek for solutions to decrease their dependence on finite natural resources. An important issue is also to evaluate how much waste a company generates throughout the life cycle of their products.

From that perspective, Corbion is among the companies that recognize that the linear economy is not working for the planet. Corbion is the global market leader in lactic acid and its derivatives and a leading supplier of emulsifiers, functional enzyme blends, minerals, vitamins, and algae ingredients. It uses its expertise in fermentation and other processes in order to deliver sustainable solutions in the areas of food production and preservation, health, and bioplastics. It is highly committed to contribute to a sustainable environment and it is actively engaged in aligning their goals with the Sustainable Development Goals proposed by the United Nations. It is within this context that this work is included.

1.1 Motivation

As a result of a great increase in the commercial trading all over the world in the last decades, packaging industry has been facing a steady growth worldwide contributing for several environmental issues. Concomitantly, awareness of consumers about the drawbacks and effects of packaging in the environment has grown. Customer’s demands are changing, they expect transparency, responsible attitudes from companies and willingness of businesses to address environmental issues in order to come up with sustainable solutions. The assessment of the environmental profile of products and its clear report to the public becomes an essential part towards the shift into a circular economy.

In Corbion it is extremely important to be able to enable customers to make conscious choices while choosing products in order to help them to reduce their environmental footprint and support the transition to a more circular economy.

So far, Corbion mainly focused in assessing the environmental impact studies in their products, aiming to perform an LCA to 100% of products contributing to the *Sustainable Development Goals* by 2025 [10]. Moreover, packaging is an essential element to safely deliver a high-quality product while avoiding losses in transport between the company and the customer. Due to this close relationship between the product and its respective packaging it is significant to assess and understand the environmental impact of the latter. The need to perform an assessment of packaging is to identify hotspots, improve greenhouse gas emission reporting and finally propose improvements to reduce environmental impact and set new realistic targets.

On this basis, the work developed with Corbion aiming the study and evaluation of possible improvements in their packaging options is of the upmost interest.

In this context, within Corbion expectations, this work aims to answer the following questions:

1. Overview of what is currently happening in the different regions regarding packaging within Corbion. What is the current packaging situation?
2. How do different packaging options compare with each other regarding environmental impact in each region?
3. What are the effects of each step of the life cycle of the different types of packaging in the overall environmental impact?
4. How can Corbion improve the impact of its packaging?

Therefore, the goal of the study is to perform an assessment of different packaging used in Corbion in order to understand what are the requirements and expectations regarding sustainability in each region. It also focuses on the quantification of environmental impact of several packaging options, through a cradle-to-grave approach to identify the most critical life stages as well as an analysis of different scenarios to study the viability of improvements focusing on the reduction of the environmental footprint.

1.2 Outline of the Dissertation

This thesis is structured in the following way: First chapter contains the introduction and motivation of the work. In Chapter 2, the state of the art gives context of what has been happening in the industry in order to facilitate the transition for a circular economy. Chapter 3 focuses on the scientific background and methodology, where the theoretical framework will be discussed. In Chapter 4, a brief market analysis is presented, where the assessment of the current situation regarding packaging and sustainability, highlighting trends and requirements, is done. Chapter 5 defines the goal and scope followed by the definition of the life cycle inventory and all the necessary data sources that were necessary for the project. Chapter 6 contains results and discussion of the environmental impact categories divided per region. Additionally, in Chapter 7, the scenarios of possible improvements are studied and discussed. Lastly, in chapter 8 the main conclusions are withdrawn, followed by suggestions for future work.

CHAPTER 2

State-of-art

Environmental issues, such as climate change and the intensive use of fossil fuels has led society to be increasingly aware of the impacts of their activities. The growing concern about sustainable production of products also implicates, between many other aspects, paying attention to packaging materials, which are essential elements of the product´s life cycle.

Transition to circular economy should bring opportunities to packaging companies to maximize value. Within this concept, in the packaging industry, companies have set sustainable targets mainly focusing on plastic packaging. This is due to plastic being a key material in the packaging industry, accounting for 26% of the total packaging production volume [11]. In order to promote action to fix the plastic system, the main industry trends have been mostly focused on decreasing the use of virgin plastic while increasing the use of recycled content, packaging design to allow reuse and recyclability as well as lightweighting in order to cut down on the amount of material that is used.

With the increase of packaging waste generation, waste management has also been a matter of concern. The European Commission set a Directive that proposes a waste hierarchy that should be followed in order to improve resource efficiency and reduce waste [12]. This directive states that the steps, in order of preference, to manage waste are a) Prevention b) Reduction, c) Reuse, d) Recycling as a preferable way of disposal, and e) Disposal processes including incineration, landfill and also leakage as it is illustrated in Figure 2.

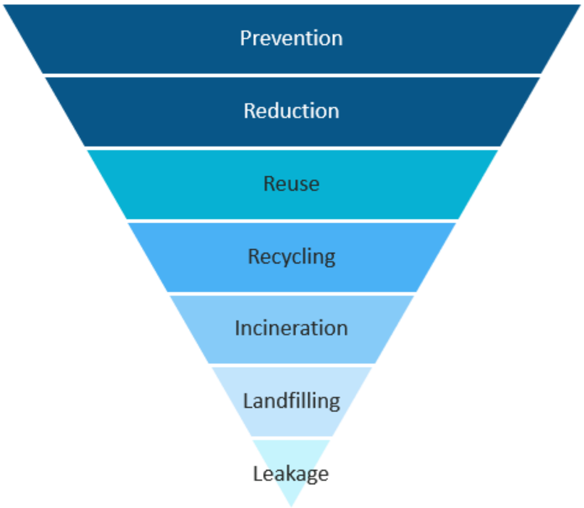

Figure 2- Waste hierarchy (Adapted from [12])

As seen in Figure 2 prevention is the base of the pyramid. Its main focus is related to the implementation of future sustainable targets and initiatives that encourage change and development within companies.

Moreover, regulations set by local governments prevent companies from over exploring resources and compel them to think of new solutions and new business models. Prevention aims to make profound changes in production, consumption patterns, and distribution. Additionally, the work alongside foundations such as the Ellen Macarthur Foundation, increases awareness, at both corporate and public level and accelerates the transition towards circular economy.

Besides prevention, one of the recommended approaches is to reduce resources and materials used by reducing weight and by eliminating unnecessary packaging. Here, the main trends are the redesign of packaging to ensure quality and functionality with the lowest environmental impact throughout their life. This is commonly called eco-design and it includes a compromise between reducing the amount of materials while maintaining the quality of packaging. It is, however, important to take into consideration that reducing materials in packaging production can result in less protected products and therefore might lead to an increase of product waste. This has been the most seen improvement as it is relatively easy to implement within existing processes and it is often financially advantageous to reduce weight [13]. Weight reduction can be obtained by reducing wall thickness, changing size packaging or improving interactions among primary and secondary packaging. One example of this is the typical plastic bottle which weight has decreased 53% since 1970 [13]. Within plastic packaging industries there has been a growing interest in alternative materials such as paper, fibers or even biobased plastic options as these plastics are associated with having fewer emissions than the fossil-based options. Eco-design is not only a trend for the reduction step, but it is present throughout the whole waste pyramid.

Through reuse packaging is used again for the same purpose as it was originally designed, consequently avoiding becoming waste and returning into the economy. This activity is being supported through innovation and re-design in order to improve packaging performance and make it more durable and robust which translates in a longer life. Reuse can also be performed by reconditioning packaging. This is an operation where the packaging in question is collected after its use and sent to a reconditioning facility where the condition of every piece is checked and it is replaced or repaired if necessary. If its condition meets the safety requirements, then the packaging is thoroughly cleaned and sent once again into the market.

Recycling is an operation in which waste materials are reprocessed into other products or materials either for the original or other purposes. It is seen as the preferred method of disposal in line with the circular economy approach [12] as it allows materials to be kept in the system and thus avoiding the need of its production. The strategy of design to ensure recyclability is mainly focused in reducing the amount of different material layers in each packaging and include recycled content. Choosing common types of plastic, common colors and avoiding combinations and mixing of materials are all actions that are done to ease recyclability. Companies are investing and exploring new technologies within the field of polymer science and selecting materials that satisfy performance requirements while increasing recyclability. A recent study done in the Imperial College of London states that “If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to shutting between 8 and 40 coal-fired power plants globally” [14]. The European Commission set the ambitious target of “recycling 75% of packaging waste by 2030” [15]. Besides the topic of sustainability, economically speaking, it does not make sense to discard plastic out of the system.“ Today, 95% of plastic packaging material value, or $80– 120 billion annually, is lost to the economy after a short first use” [11] The goal is to create an effective after-use economy.

End of life options are ranked, at the end of the pyramid. After recycling, incineration is the preferred method. Landfilling should be prevented, and it is considered to be the least sustainable waste disposal method. Once materials are sent to either landfill or incineration they cannot be reintroduced in the system. At the bottom, there is leakage which needs to be avoided.

Directives

Policymakers and stakeholders have an important role in the sustainable development of the economy. Governments around the world have been integrating environmental and industrial regulations in their policies. Although these policies might fall short compared to the needs of the current world, they are crucial in order to encourage change and development within companies.

A more sustainable world is, currently, a global concern. In 2016 governments of various countries around the world came together by the Paris agreement, the first universal binding agreement surrounding climate change as an effort to fight climate change and meet de ambition to limit global warming to 1.5°C above pre-industrial levels.

Set by the United Nations, the 17 Sustainable Development Goals are a call for action and define the 2030 development agenda aiming their alignment with the industry. These goals are universal and provide a layout to achieve a better and more sustainable world.

The new Plastics Economy Global Commitment was launched in 2018 and unites more than 450 organizations including food and packaging manufacturers and governments between others, behind an ambitious set of targets to address plastic waste and pollution at its source by 2025. This commitment endorses packaging reuse, recyclability and the decouple from finite feedstocks.

CHAPTER 3

Scientific Background and Methodology

3.1. Theoretical Framework

One of the greatest challenges that societies face nowadays, in order to avoid the environmental consequences of the current way of handling business, is to reduce greenhouse gas emissions. In order to meet this goal, it is essential to adopt a new behavior. Companies must develop accurate strategies to assess the impact that their products and respective processes have on the environment. One of the possible ways to do that is to perform a study called a Life Cycle Assessment (LCA) which adopts a life cycle approach that "takes into consideration the spectrum of resource flows and environmental interventions associated with a product from a supply chain perspective" [16]. This life-cycle thinking is used in the LCA methodology which evaluates all the existing steps in the life cycle of a certain product as well as its potential impacts on the environment [17]. This somewhat young tool, firstly developed in the late 1960s was originally applied for pollution prevention [18] but its scope is now enlarged and extended to quantify environmental performance of products through all stages of its life cycle.

Several approaches to analyze product life cycle exist; cradle-to-gate and cradle-to-grave being the most known and used. Cradle-to-gate analyzes the product until it leaves the factory gates before any transportation towards the consumer. In this way, the use stage and disposal contributions are not studied. On the other hand, cradle-to-grave considers the whole life cycle of a product: raw material extraction, manufacturing and processing, transportation, use stage, retail and waste disposal. A simplified representation of a cradle to grave analysis is showed in Figure 3.

Figure 3- Cradle-to-grave Diagram (Adapted *[19]*)

LCA is defined by the International Organization of Standardization (ISO). The ISO 14040 [17] that describes principles and framework and ISO 14044 that states a list of requirements and guidelines on how to conduct it. Creating a more uniform and standardized LCA methodology avoids the possible inappropriate use of it and the achievement of biased results. The European Union created the PEF, “Product Environmental Footprint” to adjust and establish a common methodology that is applicable worldwide. According to the ISO standards, an LCA study needs to be carried out in four phases: Goal and scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation, as described in Figure 4. LCA is used to identify opportunities to improve environmental performance, informing policymakers, governments, and organizations as well as to select relevant indicators of environmental performance [17]. *Figure 4* represents a diagram of this phased framework for the LCA.

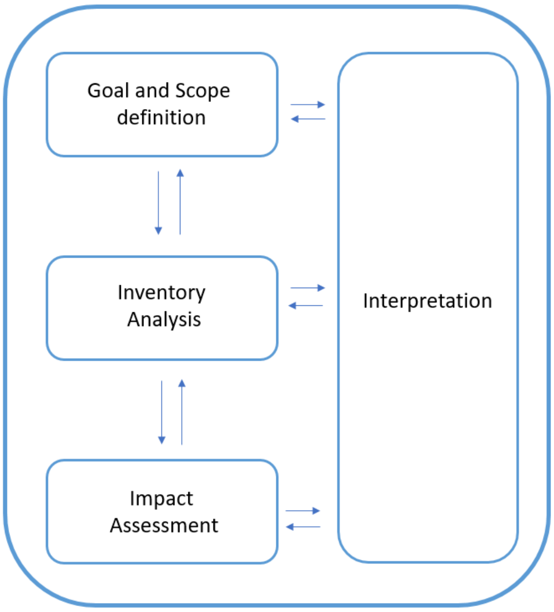

Figure 4 - Life Cycle Assessment Framework *[17]*

3.2. LCA Framework

The LCA, assisted by the Simapro software, was the used methodology to perform the quantification of environmental impacts in the present work.

a) Goal and Scope Definition

The first step when starting an LCA study, before the collection of any data, is to define the goal and the scope of the study. This is a decisive part as it determines the purpose of the assessment as well as the choices about the product system in question, the functional unit (FU) and the type of LCA study.

The goal specifies the reason for carrying out the study and it takes into consideration the intended use of the results and the target audience.

The scope of the study describes in detail the complexity of the study and demonstrates how the goal will be met.

b) Life Cycle Inventory Analysis

At this stage, input and output data are collected to allow the definition of the products that are studied. It is usually the most time-consuming stage as it requires a rigorous and extensive research and it is a critical stage since the quality of the results will greatly depend on the accuracy of the data. There are a considerable number of processes and materials available in SimaPro but there are usually a few that are not described and therefore data collection is required. The inventory analysis quantifies the system flows: resource and energy consumption as well as emissions produced throughout the entire life cycle in order to define the product systems. It is also in this phase that the system boundaries are defined.

c) Life Cycle Impact Assessment

This stage comprises the evaluation of the environmental performance of the packaging systems that were examined through different impact categories. The goal of the project will indicate which impact categories are relevant to analyze.

In the context of this project, the categories seen as more important for Corbion to study packaging systems are the Global Warming Potential, Renewable and Nonrenewable energy use, Land use and Water Use. These impact categories were chosen because they give a good overview of the environmental performance of the packaging through its life cycle. A brief overview of each impact category will be given thereafter.

i. Global Warming Potential

Global warming potential category is the most used category in the reporting of sustainability performance of companies since it evaluates the contribution to climate change, and it can be easily understood by the consumer. Greenhouse effect is one of the biggest concerns of today’s industries, and it is considered to have a direct influence in the global temperature increase of the last century. This category measures the contribution of a certain process to global warming due to emissions of greenhouse gases (GHG) into the air (most known gases being CO_2, CH_4, N_2O, CFCs, HCFCs and several halogenated hydrocarbons). Different GHG´s have different effects on global warming.

This impact category is quantified in a time horizon of 100 years. It measures how much a unit of gas contributes to global warming, measured in units of kg of CO_2 equivalents since carbon dioxide is the common standard reference for global warming. All the substances with a known effect on climate change are converted to this units in order to make comparison possible. For example, methane contribution is 25 times higher than CO_2, which means that 1 kg of CH_4 being released is 25 kg of CO_2 eq. [20]

ii. Renewable and Nonrenewable Energy Use

This impact category provides the cumulative energy demand in MJ, which measures the total energy used during the life cycle and therefore indicates the impacts of energy consumption. The quantification of the Nonrenewable Energy Use includes the subcategories of fossil (hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat), nuclear (uranium) and primary forest (wood and biomass from primary forest). Regarding renewable resources, CED includes the subcategories of biomass (wood, food products, biomass from agriculture, e.g straw), wind energy, solar energy, geothermal energy, and water (run-of-river hydro power, reservoir hydro power). [21]

iii. Land Use

Land use refers to the impacts caused by occupation, related to a continuous use, and managing of land area for human purposes. Examples of this are agricultural production, resource extraction or even human constructions. Land use is reported in area units (m^2a) and it is responsible for biodiversity loss (species, populations, ecosystems) with severe harmful environmental consequences. Examples of undesirable consequences of inadequate land use are decreasing availability of habitats and diversity of wildlife species. [22]

iv. Water Use

Water use measures the volume of water that is required throughout a certain life cycle. Water usage is usually present in all steps of the life cycle. Water might be required for the extraction of raw materials, in production for cooling, heating, or diluting or during reconditioning for cleaning purposes. The unit for this impact is reported in volume units.

d) Interpretation

The last stage of the LCA study is the interpretation stage. It includes the evaluation of results of the LCI, findings from the inventory analysis and it is where the impact assessment is evaluated in order to reach conclusions and recommendations. Through interpretation the study provides the results in an understandable and complete way in accordance with the goal and scope previously defined.

3.3. SimaPro

The LCA models used in this work were created using the software SimaPro 9.1.0.8 developed by PRé Sustainability, and the Ecoinvent v3.5 database was used to model the industrial packaging options that were studied. This database provides transparent and reliable process input and output data for a wide range of products covering energy, transport, chemicals, electronics, plastics and waste treatments. It is considered to be the most consistent and comprehensive LCI database on the market and its quality is guaranteed by a peer review process by which "data are revised by an internal LCA expert before being fed into the database" [23].

Table 1 displays the characterization methods that were used to calculate the environmental impacts. The chosen methods are internationally accepted and recommended by PEF [24]. Each impact category is represented in the following table.

Table 1- Impact categories., Characterization models and respective units

Impact Category	**Characterization Methods**	**Unit**
Global Warming Potential	IPCC 2013 GWP 100a	kg CO_2 eq
Nonrenewable Energy use	Cumulative Energy Demand V1.09	MJ
Renewable Energy Use	Cumulative Energy Demand V1.09	MJ
Land Use	ReCiPe v1.03	m^2a
Water Use	AWARE 1.02	m^3

The IPCC 2013 GWP 100a method follows the guidelines given by the IPCC, Intergovernmental Panel on Climate Change, which is the united nations body for assessing the science regarding climate change.

The Cumulative Energy Demand is a method that includes different types of renewable and nonrenewable energy resources. The CED of a product represents the "direct and indirect energy use throughout its life cycle including manufacturing and disposal of the raw and auxiliary materials." [25]

The ReCiPe method is another method for the LCIA. "The primary objective of the ReCiPe method is to transform a long list of life cycle inventory results into a limited number of indicator scores" [26]. These indicators change depending on the environmental impact that is being assessed and they are determined at two levels (18 midpoints and 3 endpoints). In this case, the ReCiPe method is used for the Land Use impact category. The indicator mid-point considers the impact in an earlier stage along the "cause-effect" chain before the endpoint is reached [27]. The midpoints considered for this category were urban land occupation and agricultural land occupation.

Aware, Available WAater REmaining, is the recommended method to perform water consumption impact assessment.

CHAPTER 4

Sustainable Packaging Market Analysis at Corbion

In this chapter the current situation of packaging used by Corbion is analysed. With this in mind, it was necessary to gather information by conducting interviews with several stakeholders across the company. Before providing any kind of suggestion for improvement, it is relevant to identify trends in the market and understand what customers are interested in. Therefore, this step of the study had as the main objective the evaluation of the current situation in Corbion highlighting main concerns, both from the company as well as from customers and understand the main trends in each region.

To carry out this assessment several departments were consulted within Corbion namely among others, Sustainability, Procurement, Environment Health and Safety, Industry and Market Directors, Quality Managers and Customer Service.

The assessment focused on the countries where Corbion has industrial facilities: Netherlands, Spain, Brazil, Thailand and the United States of America. The description of the packaging systems for each region is listed here although its definition can be found later in section 5.1.3.1 of this work. It is also relevant to note that depending on the country, infrastructures and waste management differ. Assumptions of disposal for each region are present.

4.1 Netherlands

The Corbion facility in the Netherlands, Gorinchem, focuses on producing lactic acid derivatives. The types of packaging used must be compatible with these types of products which are usually liquids.

It is worth noting that when the procurement department is choosing packaging from suppliers, already 20% of the decision falls on sustainability.

When looking into packaging, the customers of Corbion in the Netherlands have quality as the first main concern, but it is not usual for customers to suggest changes in packaging focusing on sustainability. There have been expressions of concern regarding the amount of material that is sent to disposal, for example. Additionally, Corbion in the Netherlands uses a collection service for its used IBCs. This means that when IBCs are in good condition, they are sent to a company to be repaired and cleaned and later be put into the market again.

Dutch government has put policies in place, including taxes and bans that discourage the use of landfill as an option for waste. Consequently, the Netherlands is one of the five European countries that landfills less than 5% of their municipal waste and it is recognized as having the best waste management program in Europe [28].

The packaging systems that were analyzed for the Netherlands were the high-density polyethylene (HDPE) drum of 200L and the 1000 L industrial bulk container (IBC) with HDPE, steel or wood pallet. For this study, since we are dealing with industrial waste, no landfill was considered. It was assumed that 80% of waste will be sent to recycling [29] and 20% to incineration. The exception is the disposal of steel which was considered to be recycling.

4.2 Spain

In Spain, Corbion produces lactic acid derivatives for food and pharma markets. These type of products has implications in packaging due to the extra regulations issued by the European Commission. These are (EC) No 1935/2004 setting principles of safety and inertness for all food contact materials, (EU) No 10/2011 on plastic materials in contact with food or (EC) No 2023/2006 on good manufacturing practices for materials and articles intended to come into contact with food. The strict rules related to food products will influence packaging, especially when it comes to reuse and using recycled materials. One of the consequences of this is the forbiddance to reuse packaging.

From the perspective of customers, there has been some interest in bio-based alternatives to plastic, suggesting that sustainability is already a concern. On the other hand, there are still few customers who put sustainability over topics such as price and quality. The effort of most companies related to sustainability is usually due to regulations.

The packaging options that were analyzed for Spain were the IBC’s with HDPE, steel and wood pallets, the Jerry can of 20L and the HDPE drum of 200L. When comparing it with other regions it is clear that in the Spanish site there is a different approach to disposal regarding plastic packaging. Here, a company is hired to receive plastic packaging and recycle it. For IBC’s, besides recycling, this company also provides the possibility of reconditioning. Through data sent by procurement in Spain from 2019, it was possible to calculate that near 80% of IBCs were sent to reconditioning. The ones who are too damaged to be reconditioned, the remaining 20%, are sent to recycling. All other plastic packaging, such as the HDPE drums, are sent to recycling. Regarding steel, no specific information from the sites is provided. It is assumed that 100% will be sent to recycling as disposal. This information was used to model the end-of-life of packaging in Spain.

4.3 Brazil

In Brazil, Corbion has three facilities. One of them, Campos, produces lactic acid and lactic acid derivatives for the food and the biochemicals market. The second site focuses on algae ingredients which are mainly solids (granulates) and suspension solutions. The third site is a new one which produces food ingredients.

In Brazil, sustainability is still not at the core of decision making when it comes to packaging but there is still great interest in looking at possibilities and alternatives. Once more, it is not possible to use reconditioned or reused packaging due to food grade regulations

The customers of Corbion still use predominantly smaller packaging instead of bulk, one of the reasons for this occurrence is the easier handling since smaller sized drums can be managed by one operator, while for bigger volumes more workers are necessary. In order to standardize, Brazil wants to encourage customers to purchase bigger volume packaging. Having a lot of packaging options is not ideal as it has a big impact in the production line. Additionally, another detail that reinforces that sustainability is considered by Corbion in Brazil is that it donates its used drums to an organization that collects used cooking oil while for the IBCs it also uses the collection service to send them to reconditioning.

Brazil is the 4th biggest producer of waste worldwide, in volume [30]. Disposal percentages used in this work, for Brazil, were gathered from the Ecoinvent 3.5 Database, these values are estimated based on the UN statistics. Besides Steel, all materials in Brazil will have the following disposal treatment: Unsanitary landfill 88%, Open Burning 3%, Open Dump 8%, Municipal Incineration 1%. Steel, similarly, to the other regions, is assumed to be sent to recycling. The packaging systems that were analyzed for Brazil were the IBC of wood and steel pallet and the HDPE drums of 200 L, 50 and 25L.

4.4 Thailand

Thailand facility produces lactic acid and lactic acid derivatives for the food and biochemicals markets. Sustainability is still not a priority within consumers and industry. The main criteria when choosing packaging is quality followed by price. Another aspect that is important to take into consideration when suggesting alternatives for Thailand is that in this region the number of suppliers is scarce and therefore choice is limited.

A high expectation from customers regarding quality exists. However, there is also a reluctancy in alternative packaging such as recycled materials or reconditioning which are seen as affecting quality. In Thailand, contrasting with the global trends, there has been a contrary shift when choosing packaging. Although packaging suppliers have been coming out with lighter options, there has been interest in using heavier types of packaging with bigger thickness specially for IBCs and Drums. Again, this decision is majorly influenced by the concern with quality.

Data regarding Thai municipal waste disposal policy is limited. The assumed disposal percentages were: 50% of waste ends up in open dump and 50% is sent to sanitary landfill [31]. The packaging that was chosen for Thailand was the IBC with plastic pallet, the Jerry can of 20L and the HDPE Drum of 200L.

4.5 USA

Corbion facilities in the USA produce lactic acid and lactic acid derivatives (one site) for the biochemical and food market as well as emulsifiers (liquids), functional blends (powders) and polymer additives (solid). The different type of products greatly influences the requirements for packaging due to difference in physical properties. For powder products, for instance, the compaction to avoid lumps at the bottom, the humidity to control moisture content and the segregation to make sure there is homogeneity inside the packaging needs to be taken into consideration.

Regarding packaging, the usual requirements from customers are related to safety properties. In the market of *home and personal care*, there has been an opposite shift from the ones seen in the industry. Customers of this specific market prefer pails over drums and there is a tendency of moving away from bulk alternatives in order to minimize product waste since this market usually sells very small volumes of product.

Big customers who have a large public exposure show a lot of interest in sustainability issues. These clients ask mainly for recyclable packaging, sustainable sourcing, and biodegradability. They will possibly pay more for a more sustainable alternative. Although it is a hard task, the benefits of having a more standardized process with less packaging alternatives was discussed. A possible way to achieve this would be to reduce price when customers purchase the same type of packaging to convince them to choose the same options when ordering products.

All packaging must be approved by USA Food and Drug Administration (FDA) which is responsible for public health by ensuring safety. In the US, any post-consumer resin (PCR), a plastic that has already been recycled and is ready to be used again, must be approved for food contact by the FDA. Although it is possible to use PCR in food packaging, there is still some cost-effective issues regarding screening and subsequent elimination of contaminates which contribute to the persistence of virgin material.

Regarding the disposal of packaging material, during conversations with Corbion team in the USA it was discussed that the most common way to dispose industrial waste is landfill. For this reason all materials were considered to be sent to sanitary landfill, except steel that, as for all other countries, was considered to go 100% to recycling and paper, that was considered to be 88% recycled and 12% sent to sanitary landfill. [32]

The Corbion sites in the USA have been making significant efforts in order to improve sustainability performance with some ongoing projects namely to decrease stretch film gauge from 80 to 64 gauge and another one to study the use of reconditioned 55-gallon drums. Also, in this context and although with no defined target yet, a research study with PRATT company is being developed as they are a 100% recycled corrugated provider and therefore a possible collaboration is being assessed for the near future.

The packaging that was chosen to be analyzed in the USA was the IBC with plastic, steel and wood pallet; the HDPE Drum of 200 L; the steel drum of 200 L; the pail of 5, 3.5 and 2 gallons; 25 kg capacity carton box and paper bag and lastly the fiber sack with a capacity of 1000 kg.

From the collected information, it is possible to draw the immediate conclusion that the situation regarding packaging significantly depends on the country where Corbion facilities are located. As discussed above, this difference is due to different products and packaging requirements, tradition, customer demand, regulatory requirements, different levels of sustainability awareness as well as different waste management systems.

CHAPHTER 5

Life Cycle Assessment of Packaging

5.1 Goal and Scope Definition

5.1.1 Goal

The goal of this work regarding LCA methodology is to understand, from an environmental point of view, which are the most impactful steps of the life cycle of packaging used in several regions where Corbion facilities are located and quantify its environmental impact.

5.1.2 Objectives

In LCA framework the objectives of this study are the following:

- Create a model in SimaPro for each packaging option, from a cradle-to-grave perspective.
- Quantify the environmental impact of each packaging option for all the chosen impact categories.
- Compare results and withdraw conclusions.

5.1.3 Scope

As described in the previous chapter, the different products sold by Corbion vary from one country to another. Therefore, the different production sites require specific packaging to send the products to their final destination. The specifications of each packaging depend on multiple factors such as different product physical properties, order size, customer demand and production line requirements. The properties that influence packaging decisions are usually physical state, pH, material compatibility, being tamper-proof, temperature and transport resistance.

In this work, the most relevant types of packaging options that are used in the several Corbion facilities are assessed. The studied systems are types of primary industrial packaging that are purchased from an external supplier and are filled with products from Corbion and then shipped to the respective customer. The filling of the packaging, that is, products of Corbion and consequently all its interaction with packaging are out of this scope.

5.1.3.1. General Description of the Studied Systems

This work only concerns primary packaging as secondary packaging is out of scope. Primary packaging is in contact with the goods and its main functions are protection, preservation, and distribution. On the other hand, secondary packaging refers to those that are either used for logistical purposes or to protect primary packaging during storage and transportation. Examples of these types of packaging being stretching film, labels, and seals.

From the information obtained from different Corbion sites and departments such as procurement, EHS and industry directors it was possible to conclude which packaging options were the most relevant to be studied. The chosen systems are presented in Figures 5 to 11 and are described below. A simplified diagram showcasing inputs and outputs considered to build the model in SimaPro is presented in Appendix 1. The values for inputs required to model each packaging option are detailed in Appendix 2.


Figure 5 - IBC with wood pallet


Figure 6 - HDPE and Steel Drum


Figure 7 - Jerry Can


Figure 8 - Pail


Figure 9 - Carton Box with plastic Lining


Figure 10 - Paper Bag


Figure 11 - FIBC or Super Sack

i) IBC - Industrial Bulk Container

IBC's, showed in *Figure* 5, are containers designed for transport and storage of bulk liquid or granulated substances. They consist in three main parts: an HDPE bottle housed in a steel cage that is attached to a pallet. The pallet can be made of different materials, usually of plastic, wood, or steel. In this work an IBC with a 1000 L bottle will be studied and, depending on the country, the types of pallet used will vary. Within Corbion the most used pallet is the plastic pallet.

Additionally, the steel used for the steel pallet and for the cage needs to be protected by a zinc coat in order to decrease corrosion.

ii) Steel and HDPE Drums

Drums, showed in *Figure* 6, are cylindrical containers used for liquids and powders. Steel drums (200L) and HDPE drums of various sizes (200L, 50 and 25L) were analyzed.

iii) Jerry Cans

Jerry can, depicted in *Figure* 7, is a liquid container made out of HDPE. The model developed in SimaPro for this system was done very similarly to the HDPE drum. It was considered that the values changed proportionally. The Jerry cans that were studied were of 25L and 50L.

iv) Pail

Pail is a packaging solution used mainly for dry and liquid product and it is also made of HDPE plastic. This type of packaging is usually used for smaller quantities as it can be observed in *Figure* 8. The studied pails were 5, 3.5 and 2 Gallons.

v) Carton Box

Corrugated box is used for powder ingredients and it is made from corrugated board. As can be seen in *Figure* 9, it has an inner lining made from low-density polyethylene (LDPE) for protection and to keep moisture levels under control. This box can hold up to 25 kg of product.

vi) Paper Bag

The paper bag is another paper option that is used for powder and dry products similarly to the carton box although it is made from a different type of paper, kraft paper. As shown in *Figure* 10, this bag has a plastic lining made from LDPE in the inner walls and it can also hold up to 25kg of product.

vii) FIBC

The Flexible Industrial Bulk Container, FIBC, pictured in *Figure* 11, is a bulk container whose body is most often made from flexible materials, in this case it is made out of polypropylene in a woven pattern. It is used for solid materials and these containers possess great capacities since they can hold up to 1000kg of product. It is usually referred to as super sack.

5.1.3.2. Boundaries

Given that this project aims to address a broad variety of packaging it is necessary to establish clear boundaries for each system. The boundaries will identify each stage of the life cycle and respective flows that will be considered for the results. All systems were studied using the cradle-to-grave analysis. A diagram outlining the boundaries of the general system, represented by the big purple square, is illustrated below in Figure 12.

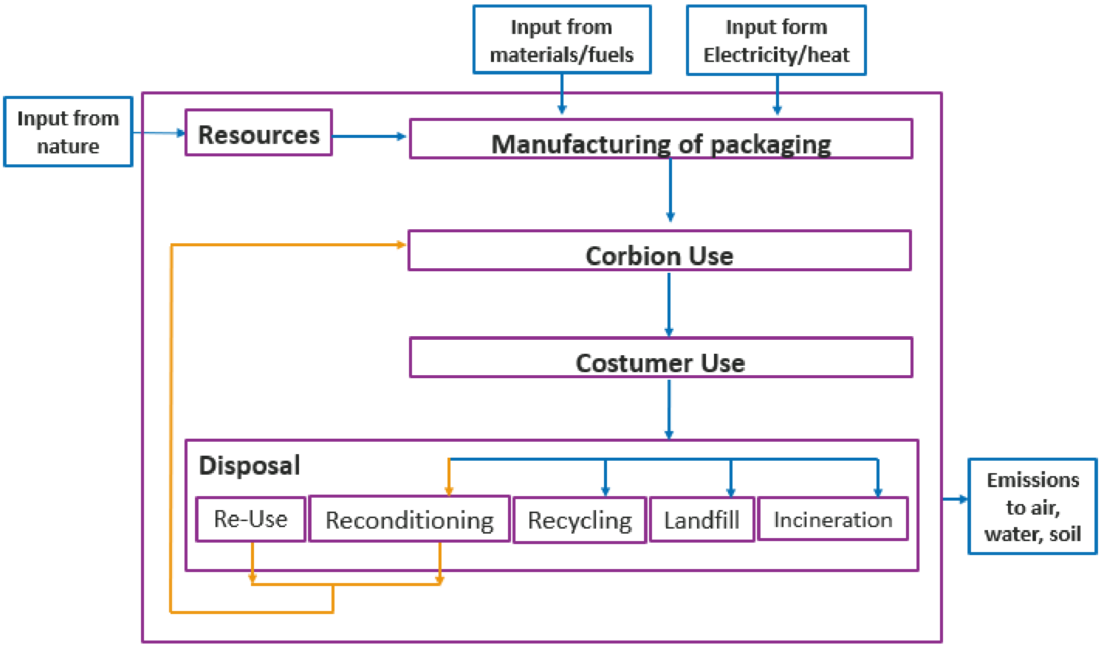

Figure 12 – Diagram of Life Cycle of the general system considering boundaries

In Figure 12 all arrows inside que system represent transportation between stages. The difference in color, blue and orange, is done to emphasize the difference between end of life. Re-use and Reconditioning are in orange as in these two options materials will return to the system after one cycle.

The inputs and outputs are depicted in the smaller blue boxes outside the system. The inputs are inputs from nature related to natural resources, inputs from materials and fuels for industrial process and electricity and heat related to energy necessary for industrial processes. The outputs are related to emissions that are sent to the environment as a result of activities throughout the whole life cycle. Disposal will depend on the studied region and what is representative of each country. It should be noted that no impacts were considered from Corbion Use and Customer Use stage.

a) Functional Unit

The functional unit of an LCA is a quantitative reference. This unit needs to be carefully defined as it is the reference for all inputs and outputs of the model and all the results will be presented in this unit. The chosen unit to present the results is per “piece of packaging”.

b) Geographical Scope

This work depicts the current situation in several locations where Corbion is present. Therefore, the geographical scope of the study considers the Netherlands, Spain, Brazil, the USA and Thailand.

The geographic scope will mainly influence types of packaging, electricity production data and waste management.

5.2 Data Sources and Main Assumptions

In this section of the project specifications of sources will be given. Data used as input in this study were both foreground data as well as background data. Foreground data refer to specific values that need to be acquired for each model. This type of data usually comes from the packaging suppliers or from experts on the subject. Background data relate to data from databases and data found in the literature. Data collection is a very important step and it is necessary to confirm that this data will serve the goal and scope that was previously defined.

The detailed description of the processes input used to define each packaging option and all the assumptions made are presented in Appendix 2.

5.2.1 Manufacturing/ Production Phase

For all packaging materials it was considered that production efficiency was not 100%. Therefore, a margin of 5% was added to all inputs of material to account for the potential material loss during production. All process data used to model material production were based on secondary data from the Ecoinvent 3.5 database while quantities of material were provided by suppliers or acquired from literature. A brief description of some material production processes, described in Simapro and that were used in the packaging models are presented below.

a) Steel Production

The steel used in the IBC´s, both for cage and pallet, and used in steel drums is low-alloyed steel and its model, in SimaPro, is defined in the Ecoinvent v3.5 database. This model considers a “consumption mix” that reflects the global industrial reality. This mix considers that 43% of this steel is recycled, produced in an electric arc furnace from scrap (electric steel) and the remaining 57% is primary steel (converter steel). Steel production using an electric arc furnace uses steel scrap as the main raw material and converts iron into liquid steel. The heat that is used to melt the metal scrap is generated from an electric arc between electrodes. It is then processed again in order to achieve the desired alloy composition. Through this process it is only possible to attain a restricted range of steels. [33].

Converter steel production, used to produce primary steel, uses a blast oxygen furnace that converts (carbon rich) pig iron into steel. During this process oxygen in blown, through supersonic injection, into the furnace containing liquid hot metal which will consequently lower its carbon content. The liquid steel obtained is further refined and alloyed to achieve the desired properties.

Most of the water used in the steel industry is used for cooling purposes.

b) HDPE Production

The bottle of the IBC and the plastic drums are made out of a high-density polyethylene plastic. There are several properties that make this thermoplastic ideal for the packaging industry. It is both lightweight and strong and it shows a high resistance against moisture as well as heat and high tensile strength. Regarding disposal, it is the most commonly recycled plastic globally.

Polyethylene is a long-chain polymer, under the family of polyolefins, that is synthesized by the polymerization of ethylene which is produced by a cracking process.

The production of olefins (C_nH_{2n}) from naphtha is through hydrocarbon cracking reaction that occurs via free-radical mechanisms. The cracking process involves applying extreme heat to ethane (C_2H_6) under controlled conditions in order to produce ethylene (C_2H_4). Afterwards, the ethylene gas needs to suffer a catalytic polymerization to produce high-density polyethylene. The most common ways to conduct this polymerization is through a slurry reactor or gas phase fluidized bed reactor in the presence of a catalyst. Afterwards, the polyethylene will go through a series of molds in order to create granulates. GHG emissions from this operation are mostly associated with fuel use.

The difference between a low density or a high-density polyethylene production is in the step of polymerization. LDPE is more flexible, and its chemical structure displays more branching. As opposed to the HDPE production, low-density polyethylene is made through a stirred autoclave or tubular reactor. Water is also used during the manufacturing process of HDPE for heating and cooling.

c) Wood Production - Pallet

For this study, wood material is utilized as one of the possible materials for pallets. The key materials for wooden pallet production are wood such as timber or particle board, and they can be made using softwood or hardwood depending on availability in that specific regional market. Usually wood pallets undergo a heat treatment in order to mitigate pests and bugs [34]. In this work, wood pallets are made from softwood, particle board as well as steel for the nails and no treatment was considered.

d) Paper Production

Paper production, more precisely kraft paper, is produced by the kraft process which utilizes chemical pulping, process by which wood chips are converted into paper pulp that is then impregnated with various chemicals in order to increase specific properties such as strength and flexibility. [35] The first step consists of debarking of wood in a rotating drum followed by cutting the logs into uniform chips. These chips are later transported to a pulping process.

Afterwards, there is the steaming step to remove the air from within the chips to facilitate the impregnation of the cooking liquor. Later, the chips are cooked in large ovens, called digesters, where the cellulosic fibers are separated from the pulp. Finally, the fibers need to be washed, drained, pressed and thermally dried.

5.2.2 Packaging Material

In order to build the model for each packaging option it was necessary to know the nature and weight of each material. These data were gathered based on specification sheets from suppliers and from literature.

It was assumed that packaging weight does not vary between regions.

5.2.3 Use Stage

The use stage refers to the use of packaging by Corbion as well as by customers after purchasing the product. The main activities associated with this phase is the packaging filling, loading and unloading. It was assumed that this phase does not contribute to the total impact, given that the majority of activities in this stage are related to the product. Due to the fact that only empty packaging is considered, any influence of product in the life cycle of the packaging is out of scope.

5.2.4 Distribution

Distribution is present throughout the whole life cycle as it allows the movement of packaging between each stage. Four different sections of distribution were considered: transport of raw materials to the manufacture facility/supplier. Afterwards, this packaging will come to Corbion where it will be filled with product and transported to Corbion's Customer. The last trip of the life cycle is the trip for the disposal facility. A diagram describing distribution is presented in Appendix 2.

All transport was done by road in a lorry. In the development of the model in Simapro, whenever transportation distances were not included in the database, the transportation by road was considered to be 100 km for each trip. For the Netherlands and Spain, there was information regarding distances between supplier and Corbion, given by Procurement. For these cases, these data were used.

5.2.5 End-of-Life

End-of-life refers to disposal of each packaging option and it is the last step of the life cycle. It is determined by material type and region. The end-of-life accounts for any burdens caused by the waste management. The processes for disposal methods that were selected in SimaPro are described in Appendix 3.

Ideally, to get the most realistic scenario, it would be necessary to understand what is the most common disposal of each type of packaging carried out by customers. This type of information was not directly available, so given the time limits of this work, disposal was selected by analyzing either average municipal waste disposal or through suggestions from Corbion collaborators across all regions.

Table 2 presents a summary of all the types packaging and disposal options that were studied and considered for each region.

Table 2 - Summary of studied systems per region

Country	Type of Packaging	Disposal
Netherlands	1000 L IBC (Plastic, Steel, Wood Pallet) 200 L HDPE Drum;	**Steel:** 100% Recycling **Other materials:** 80% Recycling and 20% Incineration [29]
Spain	1000 L IBC (Plastic, Steel, Wood Pallet) 200 L HDPE Drum 20 L Jerry can	**IBCs:** 80% Reconditioned, 20% Recycled **Plastic (not IBC) and Wood:** 100% Recycled **Steel:** 100% Recycled
Brazil	1000 L IBC (Wood Pallet, Steel Pallet) 200 L HDPE Drum 25 L HDPE Drum 50 L HDPE Drum	**Steel:** 100% Recycled **Other materials:** 88% Unsanitary Landfill, 3% Open Burning, 8% Open Dump, 1% Municipal Incineration
Thailand	1000 L IBC (Plastic Pallet) 200 L HDPE Drum 20 L Jerry Can	**Steel:** 100% Recycled **Other materials:** 50% Sanitary Landfill and 50% Open Dump
USA	1000 L IBC (Platic, Steel and Wood) 200 L HDPE Drum 200 L Steel Drum 1000 kg polypropylene FIBC 5, 3.5, 2 Gallon HDPE Pail 25 kg Carton Box 25 kg Paper Bag	**Plastic and Wood:** 100% Sanitary landfill **Paper:** 88% recycled, 12% sanitary landfill [32] **Steel:** 100% Recycled

Note: As stated previously Plastic Pallet is a pallet of HDPE.

5.3 Process Modeling of End-of-Life Systems

A brief description of the main disposal methods used in this work is now done.

5.3.1 Sanitary Landfill Process Model

Landfill, as seen in the waste pyramid is an option for waste disposal that should be avoided when considering the shift towards a circular economy. It consists on the disposal of waste by burying it in isolated places. This isolation is vital to avoid any potential contamination, through gas emissions, for the nearby population. The main challenge associated with this practice is to control leachate and gas emissions. "Landfill became an important contributor to climate change, accounting por approximately 5% of global greenhouse gas emissions" [36] and the GWG that are typically produced in a landfill environment are CH_4, N_2O and CO_2.

Depending on the kind of waste that the landfill contains, a liquid called leachate, with different compositions, can drain from waste. Once it appears, it will pass through the existing layers of waste causing the dissolution of both organic and inorganic particles, which will potentially contaminate the surrounding ground and surface water.

The process, from the Ecoinvent 3.5 database, used to model sanitary landfill in this study considers landfill gas and leachate collection system.

5.3.2 Incineration Process Model

When recycling is not possible, waste incineration is the preferred option for waste disposal. This process consists in the combustion of waste and it produces ash, flue gas and heat. Combustion plants produce steam due to the high temperature of the hot flue gases emitted from the furnace, this steam at high temperatures is usually used for heating or to generate electricity to be used in the nearby district or for industrial use.

The type of incinerator considered for this study was the moving grate incinerator, which is one of the most common technology used for incineration. One of its advantages is that is does not require prior sorting or shredding and it is suitable for large quantities of waste.

The process from the database Ecoinvent 3.5 used to model Incineration in this study does not consider energy recovery.

5.3.3 Open Dump

An open dump is a type of land disposal where solid waste is disposed without any concerns towards the environment, usually this waste is exposed to the elements and possible scavengers. Unlike sanitary landfill, open dump does not have a gas emission’s collection system therefore all landfill gas emissions are emitted directly into the atmosphere. The same case happens with leachate, as there is no leachate treatment or collection, it slowly drains into the ground. This type of disposal poses a serious threat due to a possible release of harmful substances into the surrounding environment affecting groundwater and consequently causing hazards to human health. Unfortunately, open dumps are common in developing countries due to low investments in waste disposal as well as lower availability of trained manpower.

5.3.4 Recycling Process Model

Recycling is the process of converting waste materials into new ones and it is the preferred way of disposal. The main types of recycling are chemical and mechanical recycling. Mechanical recycling is an operation which aims to recover materials, in this case plastic, through mechanical processes such as grinding, washing, separating, and drying. It is the dominating method of recycling post-consumer plastic in Europe [37] and it is the process that was considered in this work.

Chemical recycling recovers the monomers that make up the plastic object. The materials obtained through this process will be used in a posterior polymerization process in order to produce a new product. Chemical recycling has been a target of multiple research projects due to its opportunities for circular economy.

5.4 Modeling Choices

5.4.1 Pallet Use

Due to lack of data and uncertainty of what is done by the customers of Corbion, it was considered that all pallets are only used once. This means that after its first use, the pallet is sent to disposal. The disposal method, as seen previously will depend on each region.

In reality, pallets are commonly used more than once although the number of reuse cycles depend on the requirements of each client. The possibility of pallet reuse will be studied later in chapter 7.

5.4.2 Recycling Methodology

Given that the ISO standards for LCA have a large degree of freedom, there is a wide range of different views between LCA experts on how to deal with impact allocation problems and the choice of an allocation procedure is a controversial topic in an LCA study. Allocation problems can arise when dealing with materials of products that are combined with materials of other products [38]. These problems usually occur in multifunctional processes and recycling.

There are several approaches to recycling and LCA experts discuss the importance of a more uniform method for reproducibility and fairness. The main questions that arise are about the boundaries between the first and second product system and how should benefits and burdens of recycling process be shared between these two product systems.

The benefits occurring due to the recycling process are connected with the avoidance of material production. The burdens are mainly associated with energy required to perform the recycling process.

With this in mind, the end-of-life allocation that was used in this work to describe processes where recycling is present was a procedure where only the burdens of recycling are considered. Here,the benefits associated with the recycling process are only accounted for in the next cycle, therefore, as described in Figure 13 - End-of-life allocation diagram , this allocation method assumes that 100% of benefits coming from the recycling process in LC1 as well as the input of virgin material will be accounted for in the following life-cycle (LC2).

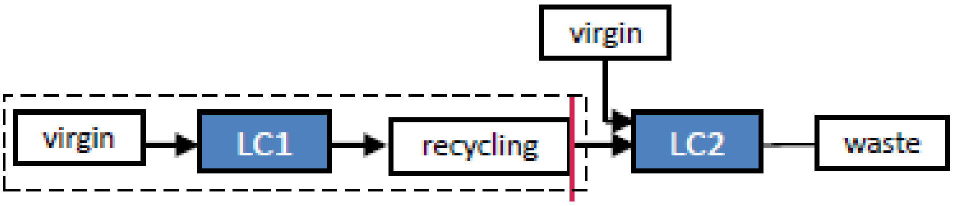

Figure 13 - End-of-life allocation diagram *[39]*

This recycling allocation assumes that the recycled material will be used for the same purpose as the original and its disadvantage is that the method simplifies the environmental impact of the “grave” stage in the first cycle, as the benefits of recycling will only be seen in the next one. The product in LC2 has both a make-up of virgin and recycled material as input for production.

CHAPTER 6

Results and Discussion

The role that each impact category plays in the environmental performance of a given type of packaging is key to understand the contribution of each step of its life cycle and consequently develop targeted action plans.

In this chapter, the environmental impact of packaging currently used in Corbion is analyzed. It is important to note that results are given per region, taking into consideration the different packaging systems, different energy sources and different disposal methods associated with each region.

Results are presented for the same capacity (volume) of packaging in order to make a fair comparison between them. For example, the impact of a 1000 L IBC will be compared with the impact of five units of 200 L drum. However, comparison between different impact categories is not possible since they have different units.

Regarding the impact categories, although more than one was addressed, global warming potential category (GWP) was studied in more depth than the others due to its unquestionable importance. GWP addresses the contribution to “the greenhouse effect” of a gas which is liberated to the environment within the cradle-to-grave period of each packaging. The greenhouse effect describes the capacity of atmospheric gases to retain heat that radiates from earth. It is obtained by measuring the amount of energy the emissions of 1 kg of a gas will absorb relative to the emissions of 1 kg of CO_2.

Energy (renewable and nonrenewable parameters) accounts for energy used for conversion of the different materials such as HDPE, steel, wood or carton into packaging (packaging manufacture). The energy parameter contains energy in form electricity and heat.

As referred in section 3.2 c) iii. Land Use is related with the use and management of land area. In this case this parameter discloses the total amount of area required during the life cycle of each packaging alternative: either it being related to the land required for the formation of raw materials or the land used for building all the necessary structures to complete each life cycle step.

The Water Use parameter describes the volume of water necessary throughout all the stages of the life cycle.

Although the life cycle of packaging consists of, as previously explained, raw material extraction, packaging manufacturing, Corbion use, Customer use and end-of-life, the report of results of its environmental impacts are done using slightly different parameters that will be now explained. “HDPE”, “Steel”, “Wood” and “Carton” parameters account for the impact of production of these materials considering extraction of the respective raw materials, transportation from the extraction site to the production site as well as the production activity itself. Transportation accounts for the distribution between the packaging manufacturing facility to Corbion and Corbion to the customer. Energy parameter considers the energy necessary for packaging manufacturing. End-of-Life accounts for the burdens that arise from the waste management of packaging. Results for all regions, which follow, are all organized in the same way and are presented in three sections. Section i) depicts the table with the results of the impacts for each packaging option. Section ii) focuses in the study of global warming potential impact of all the life cycle stages and in section iii) a given type of packaging option is chosen as an example in order to study all the environmental impacts per life step.

Note: All IBC’s have a capacity of 1000 L. In all the figures presented in chapter 6 and 7 “pallet” will be shortened for P.

6.1 Netherlands

i) Impact Category Results

The results for each studied packaging are shown in *Table 3*. Different impact categories have different units so they cannot be compared directly. Although IBC with plastic pallet and IBC with steel pallet have very similar GWP impact, it is not the case for Nonrenewable Energy Use impact category (NREU), where IBC with steel pallet holds a lower value. This difference is caused by the higher plastic content in the plastic pallet IBC due to the pallet itself. Plastic production is fossil-based so it will directly affect NREU. This influence can also be seen for plastic drums, five 200 L drum would have an impact of 4045 MJ for Nonrenewable Energy Use, a similar value to the IBC plastic pallet one.

From the values shown, one can clearly observe that Land Use and Renewable Energy Use impact are predominantly from the wood pallet IBC. These findings will be later examined.

Table 3 - Impact categories assessment results for packaging studied in the Netherlands

Impact Categories	**IBC plastic pallet 1000 L**	**IBC steel pallet 1000 L**	**IBC wood pallet 1000 L**	**HDPE Drum 200 L**
GWP (kg CO_2 eq)	177.3	177.0	136.3	30.3
Nonrenewable Energy Use (MJ)	3879.0	2845.0	2510.0	809.0
Renewable Energy Use (MJ)	127.2	157.4	689.5	18.9
Land Use (m^2)	5.3	7.5	116.3	0.7
Water Use (m^3)	34.0	34.0	25.5	5.6

ii) Global Warming Potential

Due to its importance, GWP results were chosen to be evaluated in more depth. In *Figure* 14 the cradle to grave results are presented for the most relevant packaging used by Corbion in the Netherlands.

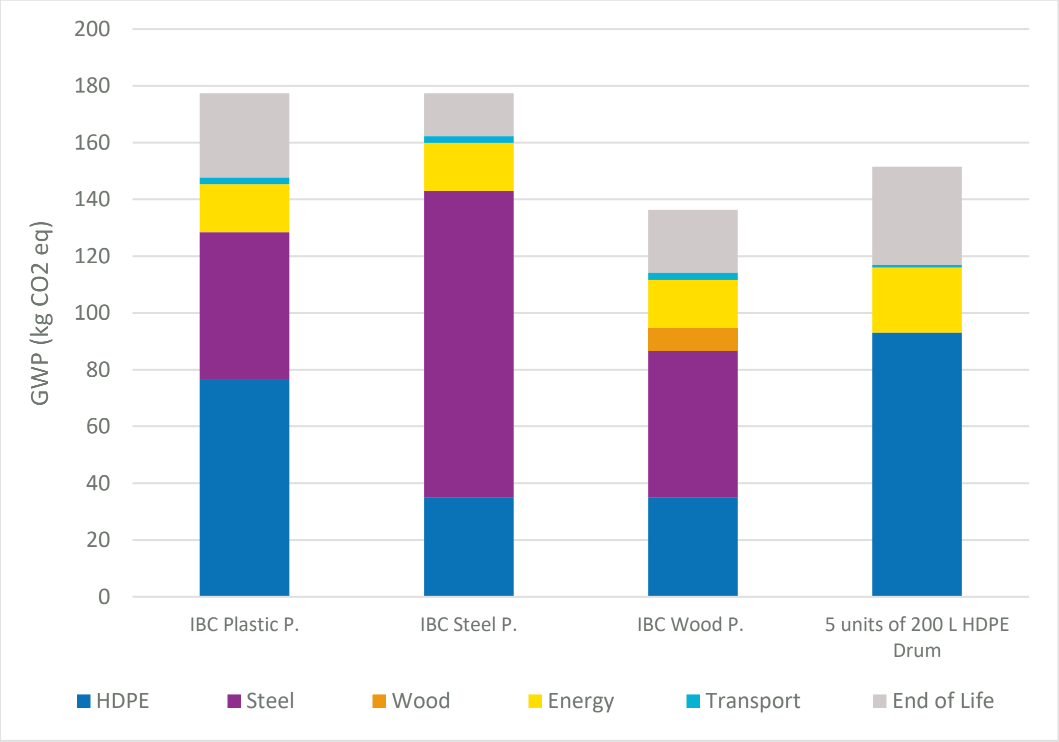

Figure 14 - Global Warming Potential Assessment of different packaging options in the Netherlands, breakdown by main contributors.

It is noticeable that for all packaging options, HDPE and steel production are the main contributors for this impact category. Here, it is possible to deduce that the most effective way to have environmental savings in this category would be to approach these two sectors.

The production of the materials that constitute the IBC of plastic, steel and wood pallets contribute, respectively, 72%, 81% and 64% for GWP impact. For the five 200 L drums, HDPE production accounts for 61% of the total GWP of this packaging.

The total impact of the IBC with plastic pallet and the IBC with steel pallet is essentially the same. However, comparing these two packaging options only on a GWP basis can be reductive and it would not be sufficient to draw conclusions. It is noticeable that between the three possible IBC's, the option with wood pallet represents a smaller impact. This is caused by the low impact of wood production compared with steel and HDPE production.

Replacing five 200 L drums with an IBC does not always translate into GWP savings. Actually, in the case of the Netherlands, results show that this exchange would be only environmentally beneficial when replacing it with wood pallet IBC. The transition from five 200 L HDPE drums to an IBC with wood pallet allows 10% of savings of total emissions. It is worth noting that this replacement might not always be possible due to food regulations.

Transport is the step that presents the lowest contribution to GWP, therefore possible savings here will not cause significant changes in results. For energy, the contribution varies between 9% of the total impact for the plastic IBC and the maximum being 15% for the drum.

The end of life considered for industrial packaging in the Netherlands was 80% recycling and 20% incineration. Only for steel, as steel is the most recyclable material, it is considered that 100% of this material is sent to recycling. Regarding end of life impacts, steel pallet IBC is the one with the smallest impact and the plastic drums have the heaviest contribution which might indicate that plastic disposal has a higher impact than steel disposal.

iii) Packaging Analysis – IBC Wood Pallet

Other impact categories must be studied to get an overview of the effect on the contributions and to better identify the opportunities to reduce impact. Since it would be too extensive to present these analyses for all packaging options, only one option was chosen to be studied in depth in order to understand the influence of each life stage in the other impact categories. For the Netherlands, the IBC with wood pallet was chosen.

Due to the different units between the categories, the results must be compared in percentages. For example, in Figure 15, for the GWP impact category, it is shown that HDPE production contributes 26% for the total impact whilst steel production has a contribution of 38%. *Figure 15* shows the weight of each life stage for the overall impact.

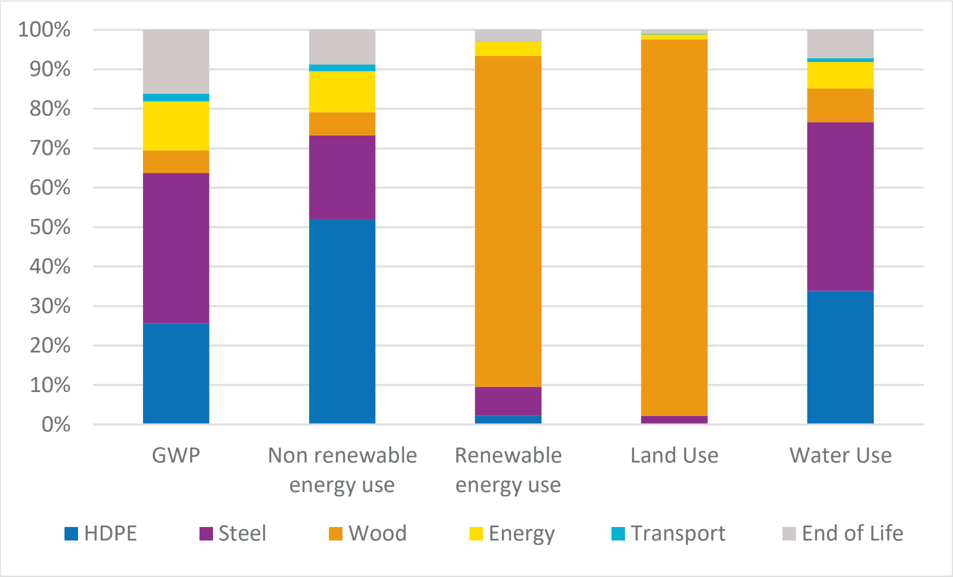

Figure 15 - Impact categories assessment of IBC with wood pallet used in the Netherlands

HDPE and steel production are the stages that contribute the most to GWP, Nonrenewable Energy Use (NREU) and Water Use while wood production stage contributes to Renewable Energy Use (REU) and Land Use.

NREU accounts for energy from fossil fuels, nuclear and biomass. Here, the biggest contribution to NREU comes from fossil fuel. As it is possible to observe in *Figure* 15, HDPE production is the main contributor since its production heavily relies on petroleum byproducts.

For REU, wood accounts for almost 80% of the total value. This high contribution results from the potential biomass energy contained in the wood. Wood is also the main contributor for Land Use. This category is especially impacted by systems that use biomass raw material. It refers to the impacts of occupying and managing land for human purposes and unlike other materials, like plastic and steel, wood production requires a vast area of land for plantation to meet demand.

Water Use accounts for the input of freshwater into the system. When studying all the considered life stages of this IBC, it is possible to conclude that material production is the step that requires the highest Water Use, accounting for 85% of impact. Within this 85%. steel production is the biggest contribution and it is responsible for 42% of the total Water Use impact.

6.2 Spain

i) Impact Category Results

The following table presents the results for all environmental impact categories of all packaging options in Spain.

Table 4 - Impact categories assessment results for packaging studied in Spain

Impact Categories	IBC plastic pallet 1000 L	IBC steel pallet 1000 L	IBC wood pallet 1000 L	HDPE Drum 200 L	Jerry Can 20 L
GWP (kg CO_2 eq)	70.1	70.4	58.0	23.4	3.0
Nonrenewable Energy Use (MJ)	1632.0	1216.0	1130.0	799.0	102.0
Renewable Energy Use (MJ)	96.5	98.8	299.9	31.7	3.7
Land Use (m^2)	2.6	3.2	42.5	0.4	0.0
Water Use (m^3)	25.0	24.1	22.2	6.9	0.9

When evaluating the energy used during the lifetime of packaging, NREU is prominent. The results of this category stand out when looking into the drum and jerry can options which require a much higher HDPE plastic content for the same volume of product than the IBC's.

When comparing plastic pallet IBC with the 200 L drum (five units) and Jerry can (fifty units), they require more 21.5% and 57% of plastic content respectively. This confirms that the higher NREU impact is due to HDPE production. This is a strong reason to discourage the use of smaller packaging. By switching from a 200 L drum to a plastic pallet IBC it would be possible to decrease the Nonrenewable Energy Use by 60%.

ii) Global Warming Potential

Concerning GWP, similar conclusions can be withdrawn for both Spain and the Netherlands. The absolute value being, however, higher for the Netherlands. Due to the presence of Corbion in the food and pharma industry in Spain, only new packaging can be used. It is worth mentioning, however, that in Spain IBC's are sent for reconditioning at the end of life which means that they will be reused again by other companies. Although reconditioning is a step that happens in the end of the life cycle, it is not a disposal method by definition. Therefore, it was decided to not include its impact in the "end-of-life" step and present it separately. The "reconditioning" life stage in this model accounts for transportation between users and reconditioning facility, solution used to clean the IBC bottle [40] and electricity used in this process [41].

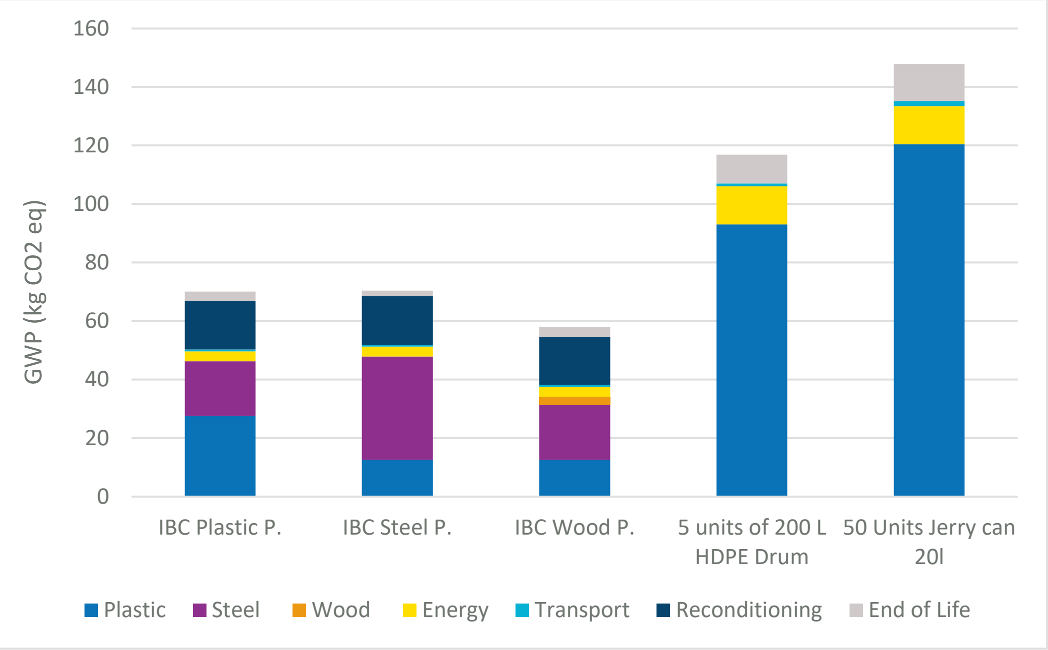

Figure 16- Global Warming Potential Assessment of different packaging options in Spain, breakdown by main contributors

Regarding the IBC's, as seen in *Figure 16*, the IBC with wood pallet is the least impactful out of the three possible options. When looking into the impact of using smaller packaging, such as the jerry cans, it is clear that they represent higher burdens to the environment. In this case, for the same volume of product, higher quantities of HDPE need to be produced. Due to its higher plastic content, the end of life of the jerry can is also slightly higher than the typical IBC.

As previously mentioned, one possibility of reducing emissions could be to increase packaging size. One example of this would be to use the drums instead of the jerry can. Simulation results show that this shift in Spain would mean a decrease of 20% in emissions.

iii) Packaging Analysis – IBC with Plastic Pallet

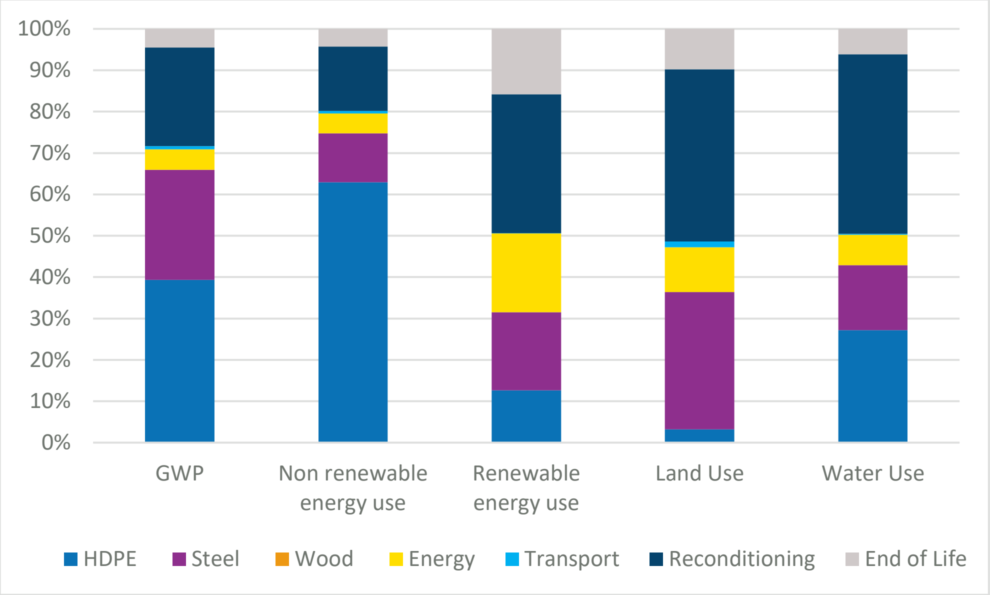

Figure 17 - Impact categories assessment of IBC with plastic pallet used in Spain

For Spain, the packaging analysis focuses on the IBC with plastic pallet. Same conclusions as for the example of the Netherlands can be withdrawn for Nonrenewable Energy Use. Spain has an additional parameter in its life cycle, reconditioning. As shown in *Figure 17*, reconditioning is the most impactful sector for the categories REU, Land Use and Water Use contributing 34%, 42% and 43% respectively for the total impact. In addition, for Water Use impact category, the contribution of 43% from reconditioning can be explained due to the water present in the cleaning solution used to eliminate residues from IBC bottle.

6.3 Thailand

i) Impact Category Results

In Thailand, the IBC with plastic pallet is the only type of IBC that is used. Clients from this region prefer their products shipped in smaller containers and therefore the other packaging alternatives that were studied were the 200 L HDPE drum and the 20 L Jerry can. Results for all categories are shown in the following table.

Table 5 - Impact categories assessment results for packaging studied in Thailand

Impact Categories	IBC plastic pallet 1000 L	HDPE Drum 200 L	Jerry Can 20 L
GWP (kg CO_2 eq)	154.9	25.1	3.9
Nonrenewable Energy Use (MJ)	3696.0	767.9	123.6
Renewable Energy Use (MJ)	100.1	12.2	1.8
Land Use (m^2)	3.0	0.1	0.0
Water Use (m^3)	35.1	5.9	0.9

ii) Global Warming Potential

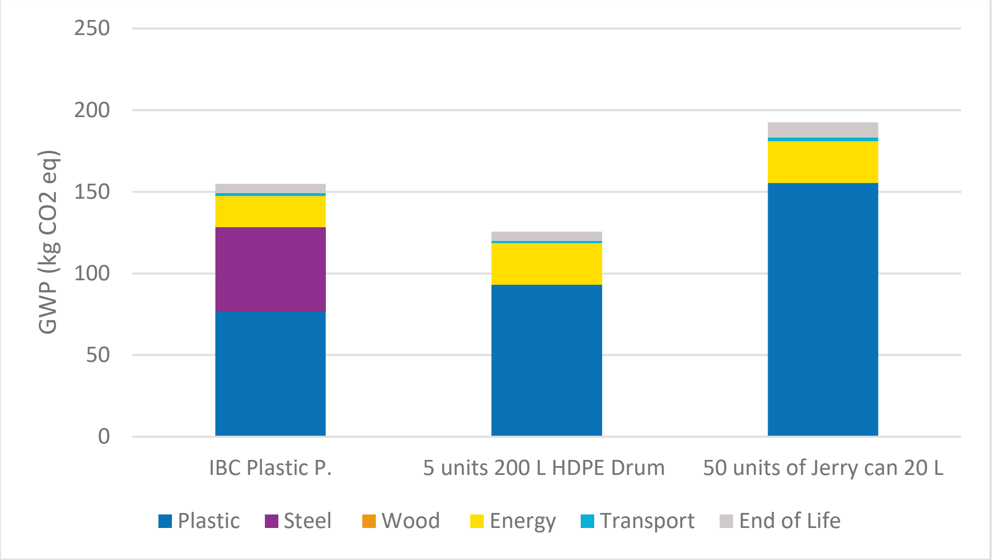

Figure 18- Global Warming Potential Assessment of different packaging options in Thailand, breakdown by main contributors.

For the same volume of product, the drum option is the one that provides the lowest GWP while the worst contribution comes from the jerry can. Again, this is due to the weight of HDPE production. Although the IBC with plastic pallet has less amount of plastic it has the additional contribution of the steel cage and therefore the overall impact will be greater than that of the drums.

One possible suggestion for this region could be to suggest to customers to change the jerry cans for the drums. With this change it is possible to reduce 35% of the GHG emissions.

iii) Analyzed Packaging – 20 L Jerry Can

The jerry can of 20 liters made from HDPE was the chosen option to be analyzed in this section. *Figure 19* allows the understanding of the magnitude of each step in the life stage.

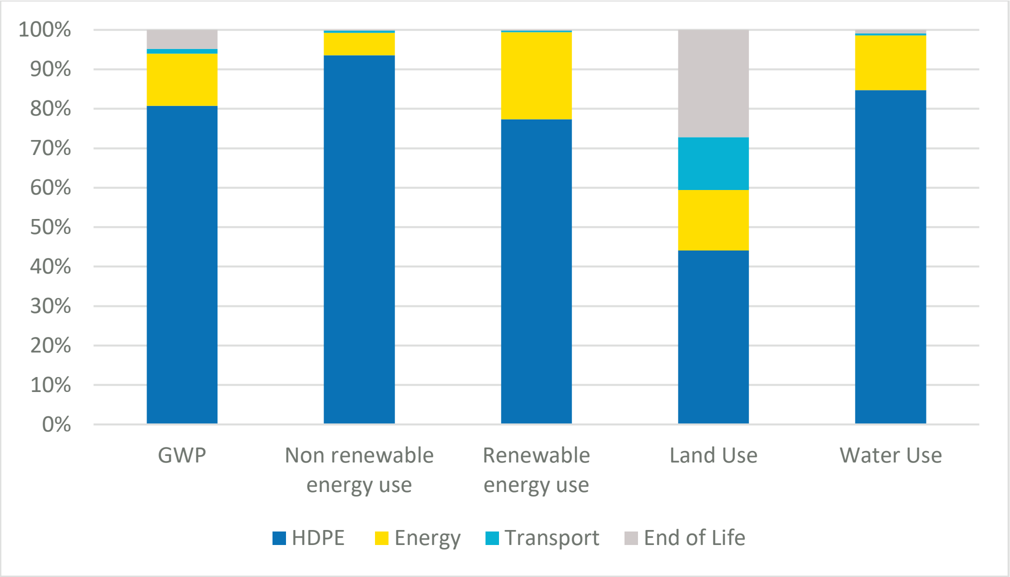

Figure 19 - Impact categories Assessment of 20 L Jerry Can used in Thailand

The jerry can is used for liquid products and it is a smaller alternative of the typical 200 L drums. From *Figure 19*, as expected, it can be concluded that HDPE production is the main contributor for environmental impact, except for Land Use where contributions are more evenly distributed. End of life has barely any impact in the categories, except for Land Use, for which it contributes 27% of the total impact. This is due to the exploration of sanitary landfill and open dump which requires the use of land area.

6.4 Brazil

The quantification of impact for packaging used in Brazil is displayed in *Table 6.*

i) Impact Category Results

Table 6 - Impact categories assessment results for packaging studied in Brazil

Impact Categories	**IBC Steel Pallet 1000 L**	**IBC Wood Pallet 1000 L**	**HDPE Drum 200 L**	**HDPE Drum 50 L**	**HDPE Drum 25 L**
GWP (kg CO_2 eq)	157.2	111.9	23.0	6.4	3.3
Nonrenewable Energy Use (MJ)	2574.0	2127.0	723.6	203.5	105.9
Renewable Energy Use (MJ)	216.6	735.1	31.6	8.2	4.1
Land Use (m^2)	5.6	113.8	0.1	0.0	0.0
Water Use (m^3)	35.1	26.0	5.7	1.6	0.8

From *table 6* it is possible to conclude that IBC with steel pallet is the option that contributes the most to GWP. Due to the existence of wood, it was already expected that REU would be considerably higher for the IBC with wood pallet. The same occurs for Land Use as the IBC with wood pallet is the main contributor.

ii) Global Warming Potential

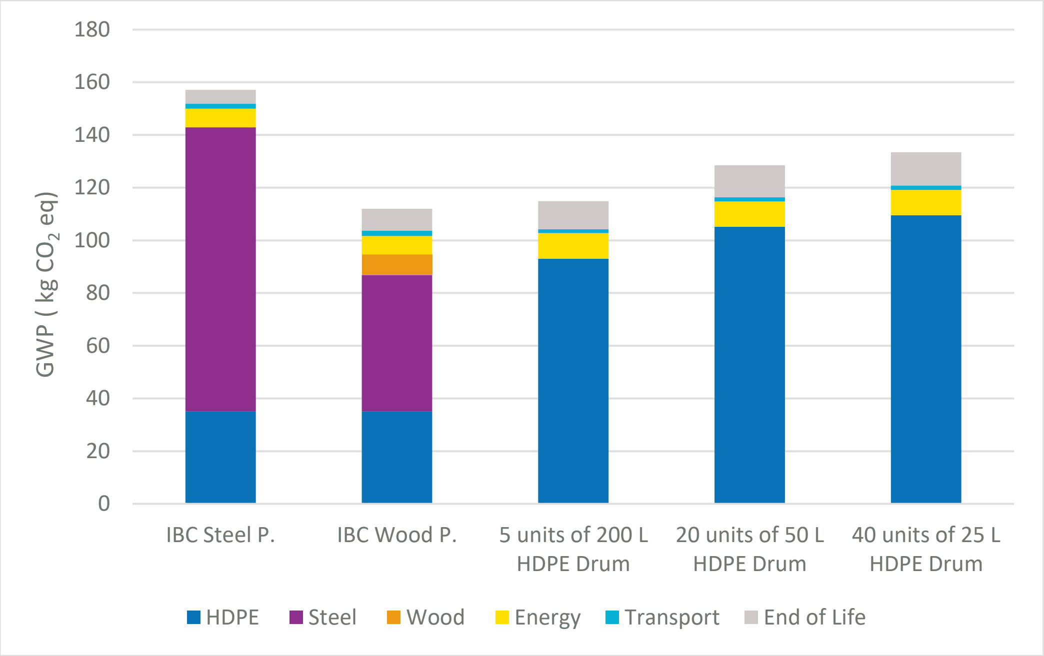

Figure 20- Global Warming Potential Assessment of different packaging options in Brazil, breakdown by main contributors

Results presented in *Figure 20* clearly show that production is the critical process associated with the environmental impact for global warming potential. For the smaller drums, 50 L and 25 L, impacts are nearly proportional and therefore in *Figure 20*- Global Warming Potential Assessment of different packaging options in Brazil, breakdown by main contributors, for the same volume of product, results are practically the same.

Again, by using the IBC with wood pallet instead of the IBC with steel cage, Brazil could decrease its impact on GWP by 29%, equivalent to 45 kg CO_2 eq per packaging. Also, the shift from the smaller drums to a 200 L drum decreases impact in 14%.

iii) Analyzed Packaging – IBC Steel Pallet

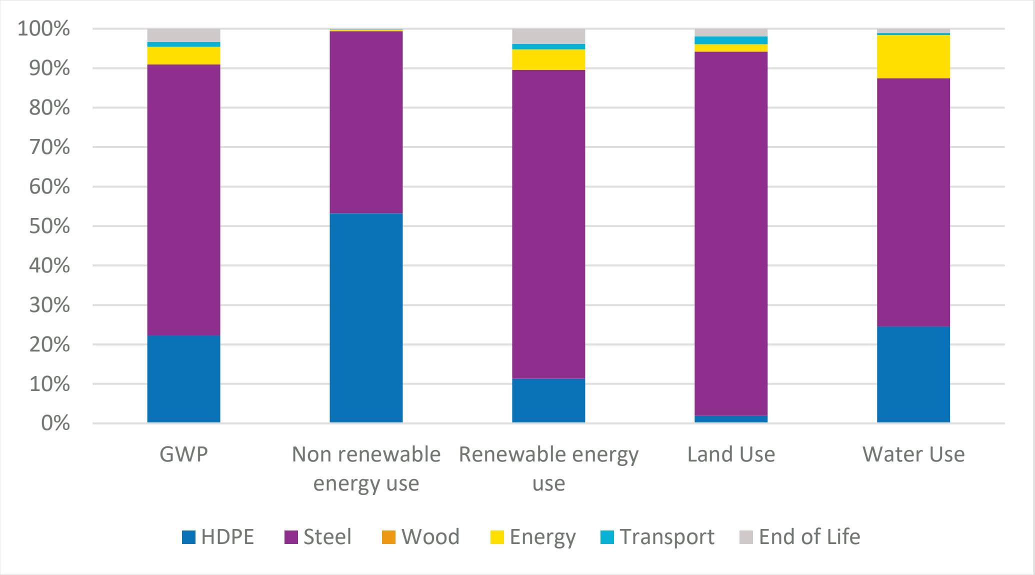

Figure 21 - Impact category Assessment of IBC with Steel Pallet used in Brazil

For Brazil, the IBC with steel pallet was the chosen packaging option to be studied. This allowed to understand the influence of steel production for the several environmental impact categories.

Steel production is the main contributor for all impact categories except for NREU where HDPE also has an important contribution due to the great use of fossil fuels in its production as previously mentioned. As presented in *Figure 21*, energy for packaging manufacture, transport and end of life stages do not show great influence in any of the impact categories.

6.5 USA

i) Impact Categories Results

The presence of Corbion in different markets in the USA results in different requirements and preferences and therefore several packaging options are relevant to be studied. In *Table* 7 all analyzed packaging along with results for each impact category are presented.

Table 7 - Impact categories assessment results for packaging studied in the United States

Impact Categories	IBC Plastic Pallet 1000L	IBC Steel Pallet 1000L	IBC Wood Pallet 1000L	HDPE Drum 200 L	Steel Drum 200L	Carton Box 25 kg	Paper bag 25kg	Super Sack 1000 kg	Pail 5 gallon	Pail 3.5 gallon	Pail 2 gallon
GWP (kg CO_2 eq)	154.6	167.8	121.0	25.0	40.6	0.7	0.5	6.0	2.7	1.9	1.0
Nonrenewable Energy Use (MJ)	3759.0	2810.0	2364.0	783.8	445.2	9.7	7.2	202.1	85.4	59.0	34.1
Renewable Energy Use (MJ)	102.4	140.8	662.1	12.8	36.8	3.7	0.2	1.5	1.3	0.9	0.5
Land Use (m^2)	3.4	6.0	114.2	0.2	1.5	0.5	0.0	0.0	0.0	0.0	0.0
Water Use (m^3)	32.3	33.1	24.4	33.1	8.4	0.1	-0.1	1.7	0.6	0.4	0.0

Note: Approximate conversion of gallons to L. 5 gallons = 19.0 L; 3.5 gallons = 13.2 L; 2 gallons = 7.6 L

ii) Global Warming Potential

As USA market covers different types of packaging the results are organized according to the nature of the packaged products. The results for packaging of liquids is presented in Figure 22. The first conclusion that can be drawn, from what is shown, is that the use of different materials for pallets of IBC's influences the overall GWP impact.

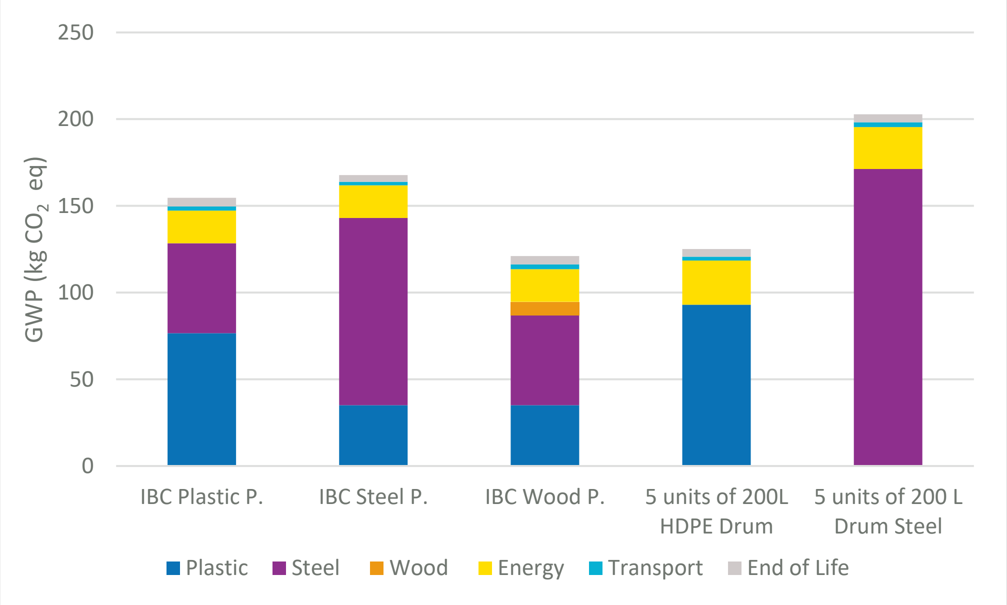

Figure 22- Global Warming Potential Assessment of different packaging options for liquid products in the USA, breakdown by main contributors

In the USA there are two kinds of drums, steel and HDPE. As shown in *Figure* 22, the steel drum has a higher GWP impact than the HDPE option. In fact, for drums with the same size, HDPE production emits 93 kg CO2 eq while steel production emits 171 kg CO2 eq. On the other hand, impacts of energy and end of life are similar between the two. Transportation is slightly higher for the steel drum as this option is heavier than the HDPE drum.

It can be concluded that a 200 L steel drum emits more 38% of emissions then the plastic drum. Thus, if there are no product or production restrictions, it is environmentally preferable to use plastic drums. It is, although, important to emphasize that these results study the impacts per one life cycle, if these packaging options were used more than one-time impacts would certainly decrease.

An overall view of all the possible packaging used for liquid products depicted in *Figure* 22 shows that the IBC with wood pallet and the 200 L HDPE drum are the most preferable options. Neither end of life nor transportation stage appears as an important contributor.

In the United States, as previously mentioned, Corbion offers a diverse selection of emulsifiers and functional blends. Most of these products are in a solid state, usually in the form of powders. These solid products require, evidently, different handling conditions than the ones for liquids due to different physical properties, so it is necessary to assess alternative packaging. In *Figure 23* the results for packaging of solids such as a woven polypropylene option (super sack), two different paper options (paper bag and carton box), a HDPE drum and different sized pails are shown.

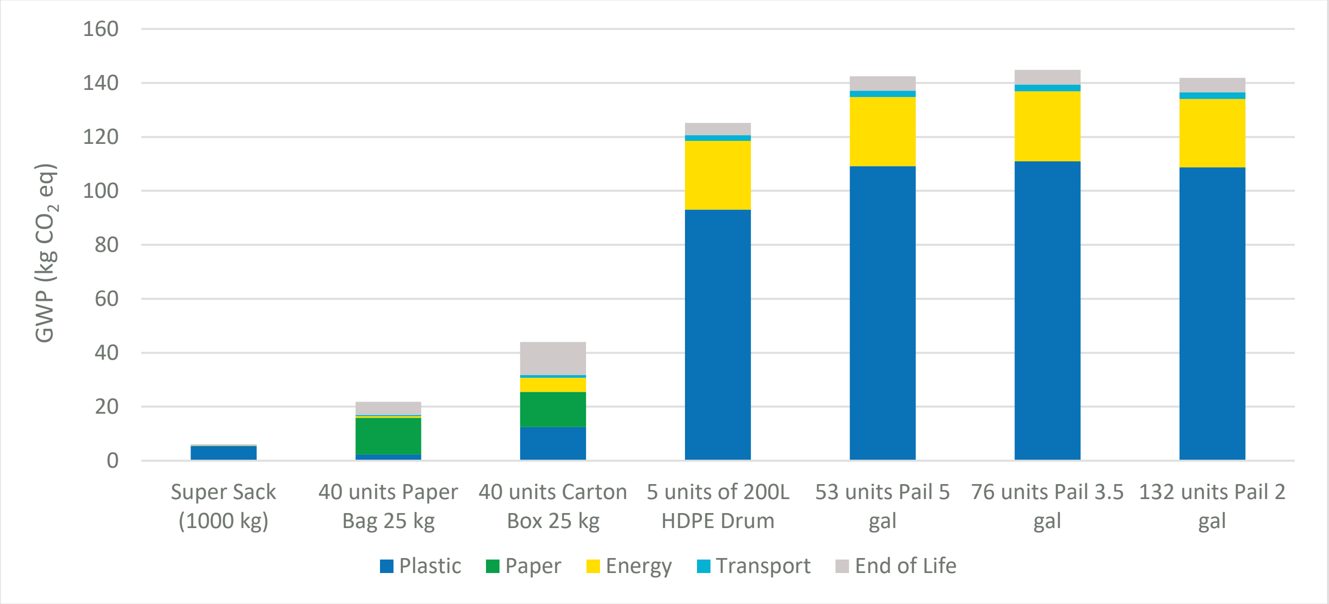

Figure 23 - Global Warming Potential Assessment of different packaging options for powder products in the USA, breakdown by main contributors

The aspect that draws more attention is the significant distinct results between the several packaging alternatives. Unquestionably, those results state that both paper options offer a much lower impact when compared to the HDPE options. Following this trend, there is, currently, an ongoing conversation, within the industry, around plastic versus paper options and all of the possible existing advantages and disadvantages.

The main contributor for GWP is plastic production due, as previously emphasized, to the use of fossil resources contrarily to paper production. Therefore, when replacing plastic for paper, the production stage will contribute significantly less to GWP.

The super sack option, also designated by flexible IBC, displays the lowest impact of all alternatives. This low contribution for GWP is due to the low amount of materials which are needed to achieve a big volumetric capacity, this being possible due to the characteristic woven pattern. These results meet the conclusions drawn by the *Institute for Energy and Environment Research* which confirm that flexible packaging plays a key role in prevention of packaging waste and mitigation of global warming [42]. For the Super Sack, the used content of plastic is 17 times less than the HDPE drum and 20 times less than the 5-gallon pail.

As to the three studied pails, the impact is the same. This occurs because inputs for the same volume of pails were directly proportional and therefore the impact on GWP is also the same. The shift from the carton box to the super sack has been considered before in the USA. This change, besides saving 90% of emissions for GWP would also provide less landfill volume which has a positive impact both in sustainability as well as in cost.

Another study that has been conducted in Corbion USA is the possibility of switching from carton box to paper bags. As shown in *Figure 23*, regarding the GWP, this switch would be environmentally beneficial as it would provide a decrease of 50% of emissions.

The pails are the smallest alternative, about 53 units of 5 gallon being necessary to transport the same amount as one super sack. They would require a high amount of high-density polyethylene that translates in high amount of GHG emissions.

iii) Analyzed Packaging - FIBC

For the USA, the Super Sack was chosen for further analysis in order to know its contribution on the other impact categories. In Figure 24, it is shown that this option has a very low impact and thus the Super Sack was chosen for further analysis as it was important to understand the behavior of its life cycle for the other impact categories.

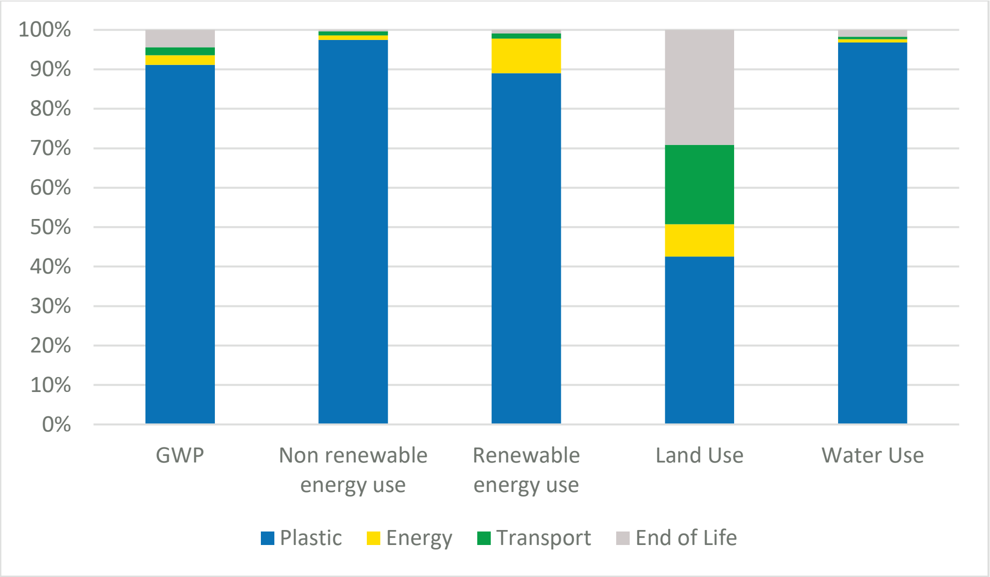

Figure 24 - Impact category Assessment of FIBC in USA

Figure 24 shows the contribution of each stage of the life cycle of the Super Sack/FIBC towards the impact categories. Plastic production is clearly the stage that produces the most impact. Propylene plastic production accounts for 91%, 97%, 89% and 97% of the overall impact for the GWP, NREU, REU and Water Use impact categories respectively. Transportation accounts for 20% of all Land Use contribution. Again, similarly to what was seen for Jerry Cans from Thailand, end of life has a significant contribution for Land Use due to the use of land for sanitary landfill.

CHAPTER 7

Improvement Scenarios

The packaging options that are currently used in the various regions where Corbion is present were studied in the previous chapter.

One of the aims of this project is to propose possible improvements in packaging management aiming the minimization of environmental negative impacts. Therefore, in order to fulfill this goal various scenarios were studied in this chapter. These scenarios study possible changes in packaging options and evaluate the influence of these changes in global warming potential impact category. Due to the big variety of different packaging options involved, for each scenario only one or two options were considered.

All scenarios were studied and modeled for the Netherlands except for the scenario 7.7, *Carton Box without lining,* which was analyzed for the USA. As previously, all the scenarios were built under the scope of SimaPro.

7.1 Recycled Plastic

One sustainability trend in the packaging industry is the shift towards recycled materials. This shift enables the use of less energy in production due to the fact that the material already exists in the system. Whether plastic is able to go into recycling or not depends if it is clean and if it has been sorted correctly. If these requirements are met, the HDPE plastic will go into recycling where it will go through a series of steps such as the washing, shredding, melting and finally the pelletizing step where plastic will be converted into granulates.

From previous results seen in Chapter 6 of this document, it can be concluded that HDPE production is a very impactful life stage. In this section, the consequences of decreasing the amount of virgin HDPE and substituting it with recycled HDPE were studied. The option of having a 200 L drum made of 50% recycled HDPE was considered. This amount of recycled content for drums is already found in the market [43]. A comparison between GWP for the two drum options is shown in Figure 25.

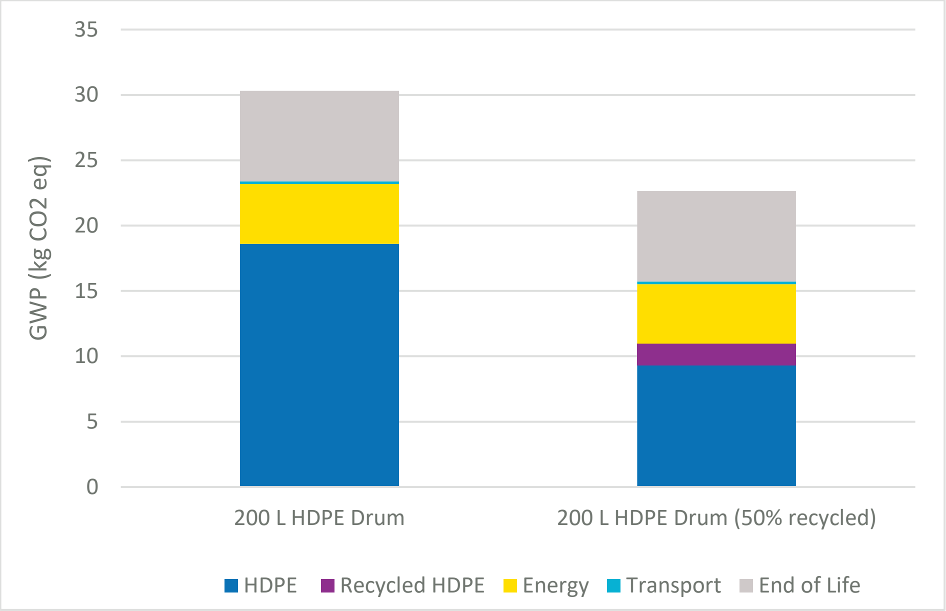

Figure 25 - GWP assessment of HDPE drum considering 50% of recycled content

In this case, results indicate that by using 50% recycled material for the drum, 4.2 kgs of virgin material are saved thus resulting in a reduction of 41% of emissions. It is also worth noting that while production of 4.2 kg of virgin HDPE emits 9.4 kg CO_2 eq, the production of the same amount of recycled HDPE only emits 1.7 kg CO_2 eq.

For the IBC with plastic pallet option, the same recycling content of 50% was assumed. A 100% virgin HDPE IBC, an IBC with 50% of recycled bottle and an IBC with 50% recycled plastic pallet and bottle were studied, the results being presented in Figure 26.

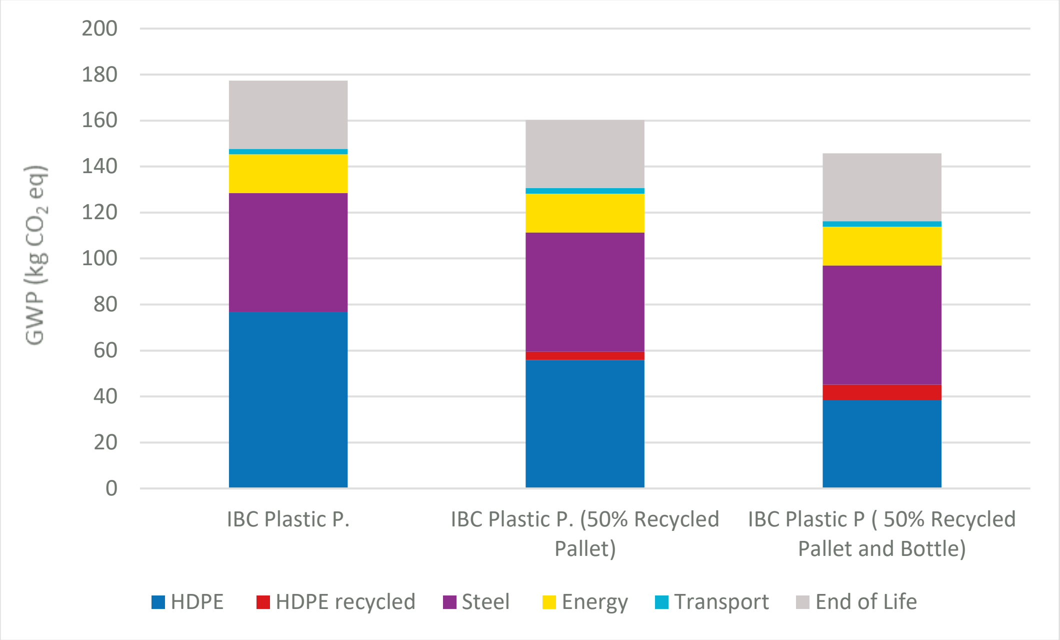

Figure 26 - GWP assessment of IBC with plastic pallet considering different recycling content

Due to the fact that the only difference between the models was the content of recycled HDPE, it was already expected that the only difference in results would be in the HDPE production stage. Similarly, to the case of the drums, it is noticeable that the production stage of recycled HDPE is much lower than that of the production of virgin HDPE.

Additionally, for the IBC with 50% recycled pallet and bottle the same amount of virgin and recycled plastic is being produced. In this case, we have 17.5 kg of recycled plastic and 17.5 kg of virgin plastic and, as it can be seen, the impact of their production is considerably different. Virgin HDPE production has a contribution of 38.3 kg of CO_2 eq while recycled HDPE has a contribution of 6.8 kg of CO_2 eq.

Another result that stands out is that if a new steel cage, a virgin HDPE bottle and utilize a pallet with 50% recycled content, there is a reduction of around 10% in GWP category. If, besides the recycled pallet, a bottle with 50% recycled content is used, then the reduction reaches 18%.

7.2 Steel vs. Recycled Steel

It has been concluded, from previous results, that steel production is one of the largest impactors of GWP in the life cycle of the studied packaging. Thus, it is relevant to examine the effect of using recycled steel and study how recycling might affect its contribution to greenhouse gas emissions. This study is particularly relevant as, cited elsewhere, “The steel industry is responsible for about 5% of greenhouse gas emissions globally, making it one of the highest-emitting industrial sectors” [44]. It is known that steel is one of the most recycled materials and it is 100% recyclable [45]. Although currently scrap-based steel production cannot absolutely substitute virgin steel production due to quality requirements, the option of having a 100% virgin steel drum was considered in this study for comparison reasons. Thus, the extreme scenarios were presented, i.e., the utilization of 100% virgin material in steel production or in alternative, 100% recycled steel made from steel scrap.

As presented in section 5.2.1 of this document, the process model to describe steel, selected from the Ecoinvent database in SimaPro, considers an average *consumption mix* of recycled and virgin steel used in the industry, therefore, in the first column of Figure 27, "IBC Steel P.", considers that 43% is recycled steel and 57% is primary steel.

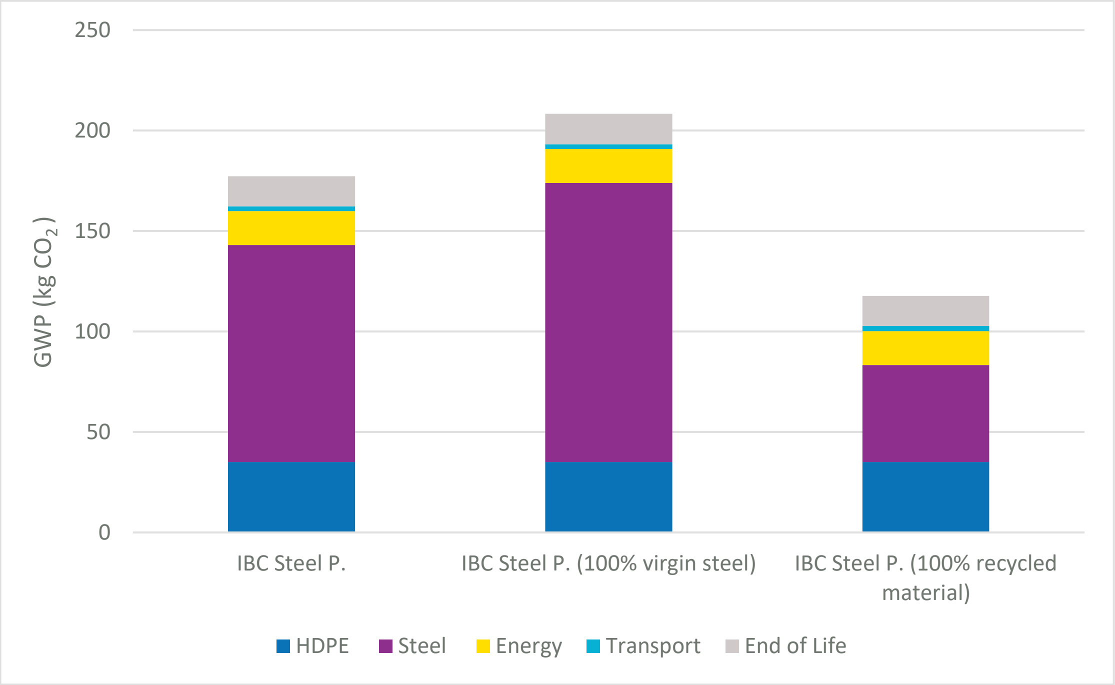

Figure 27 - GWP assessment of the IBC with steel pallet considering different amounts of recycled steel content

Production of secondary steel from steel scrap requires a considerable amount of energy (electrical energy being the main source in the system) used in the furnace for the melting of scrap. This energy is, however, much less than the energy required to produce virgin steel [46]. *The Environmental Protection Agency* estimates that secondary steel production uses about 74% less energy [47]. It is worth noting that by using progressively more steel produced from scrap will not only reduce GWP but will also preserve natural resources by reducing the exploration of mining to get virgin ore.

It is seen from results that the manufacturing of packaging, examined by the "energy" parameter and the end-of-life stage are not affected by the use of virgin or recycled steel. Likewise, the impact of transport, as expected, does not change as it was considered that the packaging weight is kept constant. The main impact in results is seen in the production of materials, it is possible to conclude that the way steel is produced will greatly influence results.

Considering the mix used in the industry (43% recycled steel and 57% virgin steel) instead of virgin steel only, it is possible to decrease emissions by 15%. Ideally, if is was possible to reach the goal of 100% recycled steel cage and steel pallet, this decrease would be 44%.

7.3 Bio-based Packaging

The HDPE plastic used throughout this study was high density polyethylene produced from fossil fuel-based resources, such as petroleum and natural gas. Bio-based plastics represent an emerging field in the packaging industry. Bio based polyethylene can be obtained from biological resources by synthesizing the ethylene monomer from dehydration of bioethanol obtained from glucose. This glucose can be obtained from sugar cane, sugar beet and from starch crops (maize, wheat, or lignocellulosic materials). [48]

In this context, a bio-based polyethylene was evaluated as an alternative to HDPE. This bio-based PE is produced from renewable sources, sugar cane [49], and it is chemically identical to the conventional polymer derived from oil and therefore it can be used in the same applications.

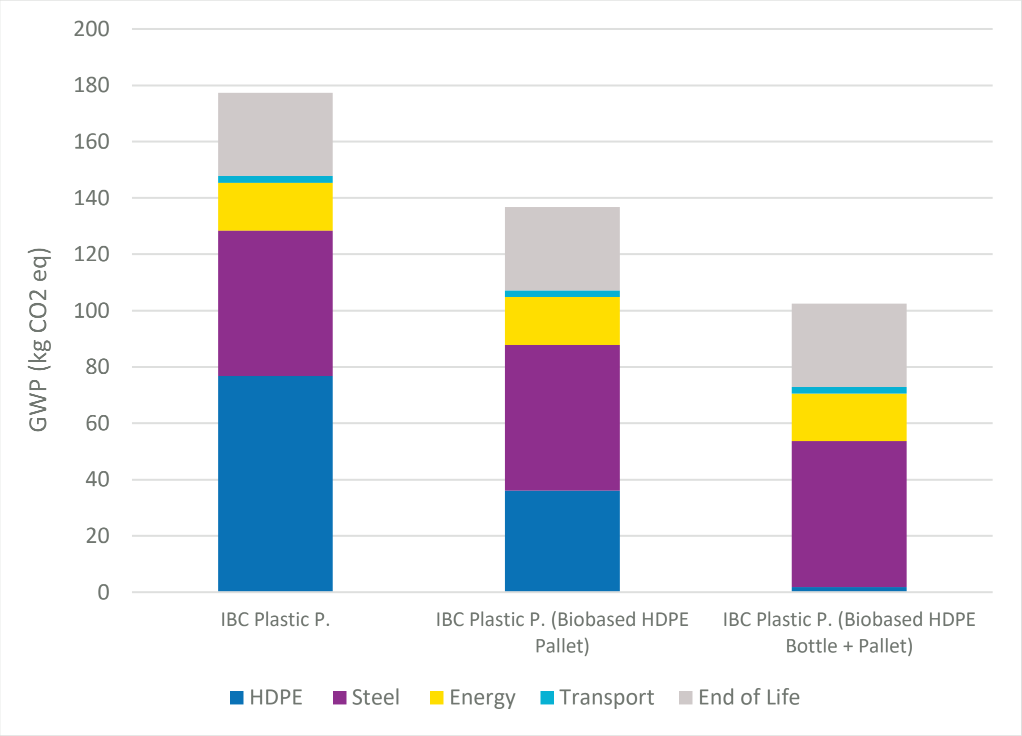

Figure 28- GWP assessment of IBC with plastic pallet considering the usage of biobased Polyethylene plastic

Figure 28 presents the global warming potential as kg CO2 eq per functional unit for 3 packaging options: IBC using both bottle and plastic pallet from fossil based HDPE and two other options, the first concerning an IBC with a bio-based polyethylene pallet and the last being an IBC where all plastic used is bio-based PE.

As can be observed, bio-based plastic has a considerably lower impact than the fossil-based HDPE. The model for bio-based plastics model was based in a study [50] which takes into consideration credits in electricity cogeneration as well as in land use change credits. The accounting of these credits reduce impacts and it is part of the explanation for the significant difference in the results. The HDPE production contribution also decreases massively with the use of biobased PE due to the avoidance of fossil-based resources.

These results demonstrate that the use of bio-based plastic reduces emissions associated of each packaging, allowing 23% of reduction when changing the pallet and reaching 42% when replacing both bottle and pallet for bio-based options. This reinforces the conclusion that the use of bio-based materials reduces greenhouse gases, enabling to shift away from fossil resources.

Although there are several biobased alternatives only a small fraction has reached the market. One of the major challenges of this field is associated with the cost of production and processing. There has been a lot of research surrounding the influence of these biobased alternatives on land use impacts due to the need of agricultural land and forest, but this impact was not considered for this work.

Besides bio-based polyethylene, another promising bio-based alternative is polylactic acid (PLA). This material will not, however, be analyzed in this work as PLA does not have the same physical properties of PE and therefore it could not directly replace it. If there is an interest in the use of this material, compatibility studies need to be performed.

7.4 Pallet Reuse

In this work, for the results presented in chapter 6, it is assumed that all pallets were sent to disposal after one use although in the industry pallets are often reused. This scenario studies the influence of pallet reuse in the GWP impact category.

It is difficult to precise how many reuses a pallet can be subjected before it needs to be sent to disposal. This will depend on each market as it shows different handling requirements, distinct carried weight on each pallet, as well as different travel distances. These are some example of factors that certainly influence the durability of each pallet and consequently influence the number of possible reuse cycles. According to literature reports [34], wooden pallets usually perform between 5 and 30 cycles while plastic pallets have a longer lifetime expectancy, lasting between 20 [51] to 100 cycles. Regarding steel pallets, some reports [51] state that they can be used for 2000 reuses whereas some other [52] states that the maximum is 1000. The present scenario is done using the average reuse times of each pallet, 60 cycles for the plastic pallet, 17.5 cycles for wood pallet and 1500 cycles for steel pallet.

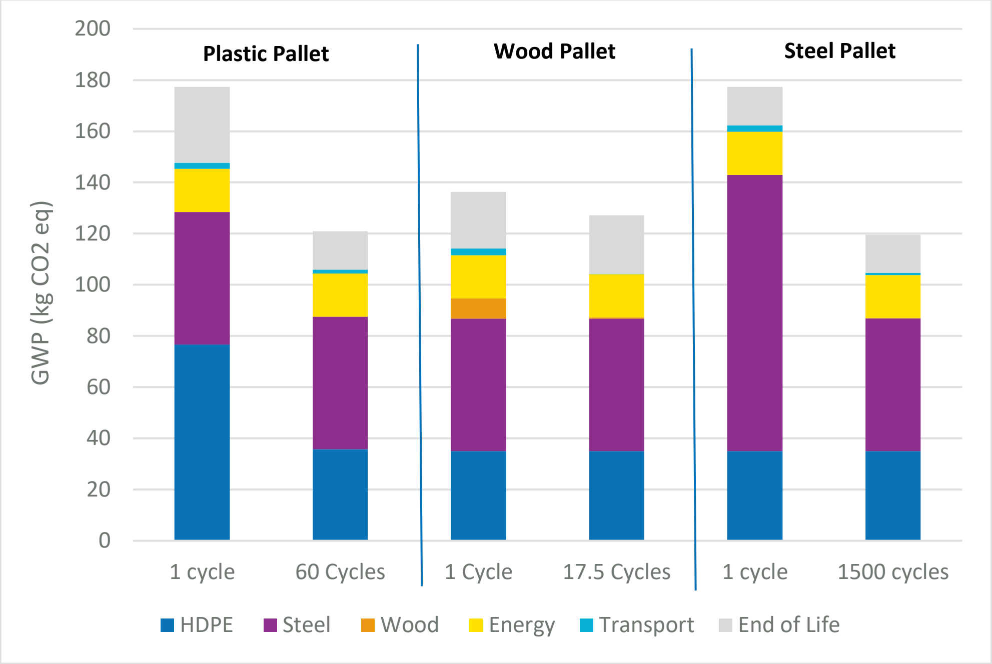

Figure 29 - Comparison of GWP impact assessment of IBC varying the reused times of each pallet

Due to lack of information regarding the fraction of energy which is used solely for the pallet production, it was assumed that the energy impact is constant and that it is not affected by the reuse of pallets. In reality, the energy necessary to produce each pallet would decrease with the increase of reused cycles. Therefore, this assumption implicates that the GWP of the reused option would be slightly lower than what is presented.

The results, shown in Figure 29, indicate that the most affected life steps by reuse of pallets are production and transport for the three pallets and additionally end of life for the plastic pallet. This result was to be expected, if a pallet is being used more than one time, it implies that less material is being used per life cycle which consequently affects the environmental performance. Looking into the case of the plastic pallet, if it is being used 60 times it means that for 59 life cycles there is no pallet production. Not only HDPE production decreases but transportation is also less, as trips from pallet production facility to the customer have been eliminated.

When looking into the end-of-life of IBC’s, plastic disposal is the most impactful. For instance, for the IBC with plastic pallet, plastic disposal causes 94% of overall end of life impact with plastic incineration and plastic recycling accounting for 59% and 37% of emissions on this life stage, respectively.

For the IBC with wood pallet and the IBC with steel pallet, the plastic content does not change with reuse of pallets as pallets are not made from this material. Due to plastic disposal being the most impactful type of disposal, the end of life contribution, in these two cases, is not greatly influenced by reuse.

Reusing pallets, considering average number of reutilization cycles, results in a decrease of 53%, 94% and 52% of material production impact for plastic, wood and steel pallets respectively. As it is seen from results, in percentage, the reduction of wood production impact is more significant than that of plastic or steel. This can be explained by the fact that wood production parameter only considers pallet production, as opposed to steel and HDPE production which also consider cage and bottle production respectively. Therefore, any change in wood pallet production will affect the whole wood production contribution while a change in plastic pallet will affect only a portion of the HDPE production.

Also, given that wood production has a very small impact when comparing with the emissions of steel or plastic production, any decrease of impact on this stage does not create a significant change in the total results. The difference of GWP impact between no reuse and reuse of wood pallet was only 6%. For the plastic pallet and steel pallet, the total quantification of savings for this category was 32% and 33%, respectively.

As previously seen in the results section in chapter 6, IBC with wood pallet was shown to be the best IBC option in respect to GWP impact. This scenario shows that this needs to be assessed with care as this result will be influenced by pallet reuse. From Figure 29, one concludes that if it was possible to reuse plastic or steel pallets their GWP impact would actually be lower than the IBC with wood pallet. Therefore, in order to better understand the real impact of packaging in Corbion it is necessary to investigate how pallets are being handled by their customers.

7.5 Reconditioning of IBCs

As it was mentioned before, there is a collection service of IBC’s that is regularly used by Corbion. In Spain, for example, reconditioned IBC’s are not allowed to be used due to regulations, but new IBC’s, after one use are sent to a recondition service.

In this section, the aim is to understand the effect of using reconditioned IBC’s on GWP impact. The IBC with plastic pallet was the chosen IBC to perform this scenario.

Given the information provided by Corbion Spain, it is only possible to recondition an IBC five times before it needs to be sent to disposal. Additionally, for the inputs necessary to model the IBC, it is necessary to consider those regarding the cleaning solution used to clean the bottle as well as energy required for reconditioning and the added transport. The composition of the cleaning solution is described in Appendix 4.

For the reconditioning scenario, it is considered that the cage, pallet and bottle are reused 5 times. This means that for 5 life cycles, production of bottle, pallet and cage will only happen one time. Contrarily, if there is no reconditioning, materials need to be produced for each use, therefore by using reconditioned IBCs, the production of new materials is avoided.

The study of the environmental impact is done per life cycle. Therefore, to model each life cycle in SimaPro, the materials necessary for production can be distributed evenly per life cycle and so, for each cycle only 1/5 of materials are considered. In order to provide a clear explanation of this scenario, an illustrative diagram of this model is presented in Appendix 1.

Results of GWP per life cycle of packaging are shown in Figure 30.

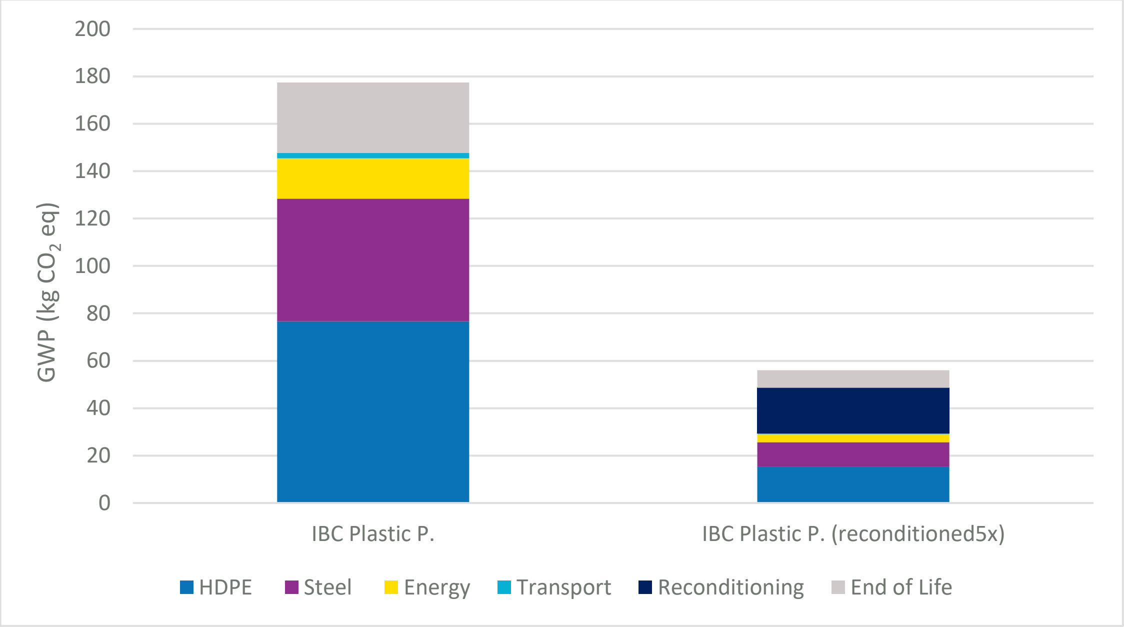

Figure 30 - Comparison of GWP impact assessment of IBC with plastic pallet new and reconditioned

The total impact is considerably lower in the case of the reconditioned IBC. The impact of the production of HDPE and steel, which are the highest contributors for emission, is 1/5 of the value for the reconditioned alternative. However, in the life cycle of the reconditioned IBC, there is an extra contributor which is *reconditioning*. This component includes the 4 batches of cleaning solution, and all the transportation associated to the reuse of pallets as described in Appendix 1. This parameter accounts for 34% of the total GWP.

Regarding the end-of-life parameter, it is seen that its contribution for the reconditioned option is substantially smaller. The explanation for this occurrence falls in the way the model was built. For the 5 life cycles, disposal only happens once, so its contribution was uniformly distributed per each life cycle.

Although there is an extra parameter that need be accounted for reconditioning, the global reduction that is possible to attain by using reconditioned IBC instead of a new one would be 68%. Therefore, whenever allowed, it is environmentally beneficial to use reconditioned IBCs.

7.6 Decreasing Plastic Content

This scenario meets one of the issues showed in the result section of this project which stated that the material production step was the most impactful step of the life cycle of packaging.

One of the most recent trends within the packaging industry is the elimination of unnecessary materials and therefore reducing the amount of plastic used in each packaging could decrease the contribution of this step. Packaging companies and suppliers are putting a lot of effort into decreasing material usage in their packaging, especially plastic packaging. This is usually done by reducing the wall thickness of packaging. Given that Corbion is not a packaging supplier, this change, obviously, cannot be done by the company. It is, however, of the upmost importance to be aware of its significance and to quantify the possible improvements in GWP.

Within Corbion, the pursue for packaging with lower plastic content was already carried out in the past. One of the suppliers of drums was able to reduce drum weight in 15% from 10 kg to 8.5 kg in the 200 L HDPE option.

Figure 31 represents the GWP of HDPE drums of 200 L with different plastic contents. The scenario was modeled by decreasing 10, 15 and 20% of plastic weight of the HDPE drum of 200 L. For this model, due to the lack of information, it was not assumed any change in electricity and therefore its contribution will remain the same for all alternatives.

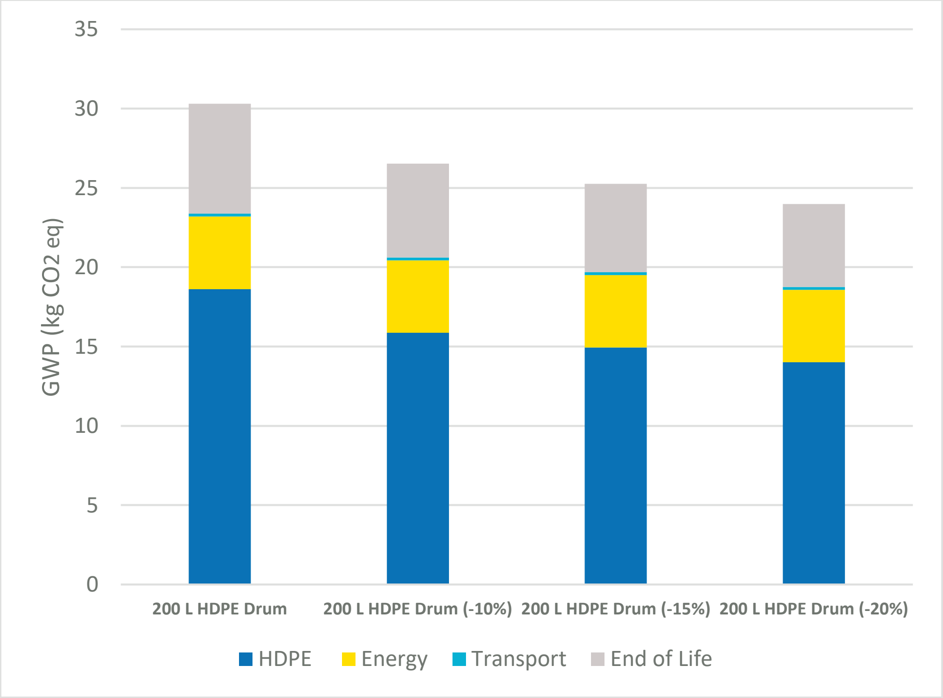

Figure 31 Comparison of GWP impact assessment of HDPE drums with different plastic content

From the results in Figure 31, it is possible to notice that overall GWP contributions decrease with the decrease of plastic content. This reduction occurs in both production and end-of-life steps. In previous results it was observed that disposal of plastic results in high values of CO_2 emissions. By decreasing plastic, less material will be sent to disposal which evidently results in a reduction of end of life contribution.

The outcome of this reduction in terms of contribution for GWP is quantified in Table 8.

Table 8 - Influence of plastic content in GWP

Plastic Reduction (%)	10	15	20
GWP Reduction (%)	12	17	21

From table 8 and Figure 31, it is seen that the reduction of plastic carries satisfactory savings of GWG emissions.

7.7 Carton Box without Lining

Eliminating the lining from the carton box could be an efficient way to decrease plastic usage. Carton box packaging option is used mainly for the transportation of powder and sometimes pasty products in several business sectors within Corbion.

Due to the fact that most of these types of products are produced in the USA, this model was developed for this geography. Plastic liners are usually used as a protection layer against exterior contamination and as a moisture barrier. It is unlikely that the scenario set here will be acceptable when considering food products and so, further studies need to be carried out to study its feasibility. Depending on the physical properties of the product, allowing the movement of moisture could cause powders to clump or paste to dehydrate. As previously emphasized, in this study only empty packaging is considered, as product is out of scope, and therefore any concerns regarding product compatibility will not be addressed.

The results on global warming potential due to liner removal are shown in Figure 32.

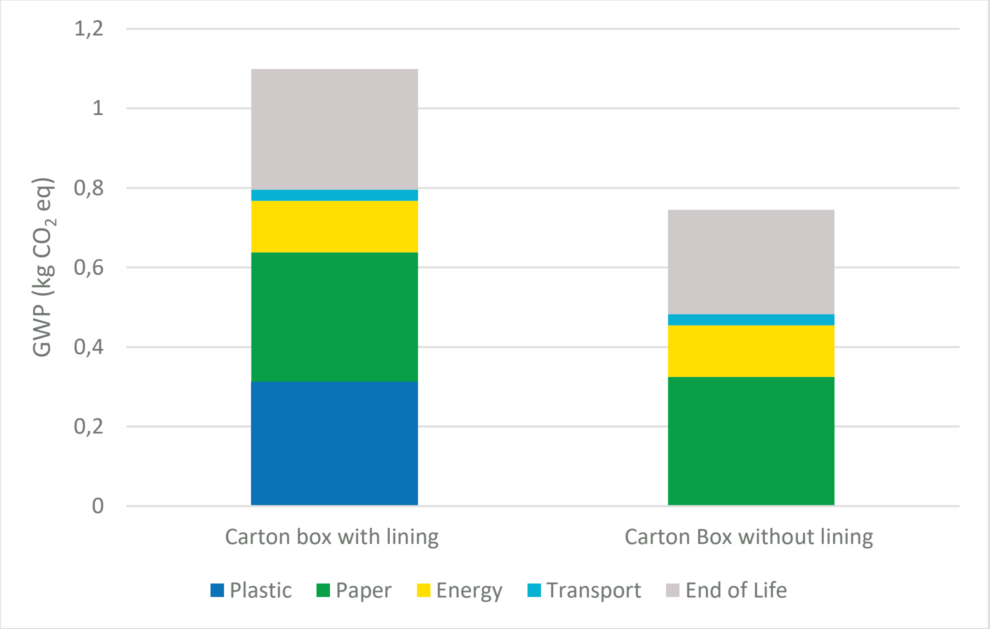

Figure 32- GWP impact assessment of Carton Box with and without HDPE lining

Excluding the plastic liner eliminated all plastic production impact. Moreover, the elimination of plastic liner also influenced end of life as the contribution of this stage decrease 14%.

Transport is influenced by distance as well as weight and as it is seen in Figure 32, its impact is not affected by this packaging change. This is due to the fact that the removal of the liner does not result in a significant weight variance and traveled distances are the same for the two presented options.

The removal of the plastic lining represents a 32% reduction in the global warming potential category.

7.8 The Circular Footprint Formula

As it was mentioned in section 5.4.2 “Recycling methodology”, there are multiple ways to approach recycling in an LCA. In order to evaluate the impact of the chosen approach in the results it was decided to use an alternative approach to model the end-of-life stage, called Circular Footprint Formula (CFF) [24]. The CFF can be used to deal with multi-functionality in recycling, re-use and energy recovery situations.

The aim of this scenario is to compare the initial allocation used for recycling throughout this work, detailed in section 5.4.2, with the approach using the CFF equation. Due to its complexity, only GWP was analyzed. The 200 L HDPE drum was the chosen packaging option to apply the CFF formula.

Equation 1 describes the Circular Footprint Formula whose parameters are described in *Table 9.*

Equation 1

$$CCF = (1 - R_1)Ev + R_1 \times \left(AE_{rec} + (1 - A)E_v \times \frac{Q_{sin}}{Q_p}\right) + (1 - A) \times R_2 \times \left(E_{recyclingEOL} - E_v^* \times \frac{Q_{sout}}{Q_p}\right) + (1 - B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}) + (1 - R_2 - R_3) \times E_D$$

This formula is divided in three main sections. It accounts for contributions of material (blue), energy (red) and end-of-life (green). The material section considers production burdens, burdens and benefits related to secondary materials input and output. Energy relates to energy recovery contribution and lastly, end-of-life consider contributions associated with disposal.

Table 9 - CFF formula parameters

Parameter	Definition	Parameter	Definition
R_1	Recycled content of material	R_3	proportion of material in the product that is used for energy recovery
R_2	recycling fraction of material	E_{ER}	emissions consumed from the energy recovery process
E_v	emissions/resources of virgin material	$E_{SE,heat}$	emissions consumed from the specific substituted energy source, heat
E^*_v	emissions/resources of virgin material assumed to be substituted	$E_{SE,elec}$	emissions consumed from the specific substituted energy source, electricity
E_{rec}	emissions/resources consumed from the recycling process	LHV	Lower Heating Value of the material in the product that is used for energy recovery
$E_{recyclingEOL}$	emissions/resources consumed from the recycling process at end-of-life	$X_{ER,heat}$	efficiency of the energy recovery process for heat
Q_p	quality of the primary (virgin) material	$X_{ER,elec}$	efficiency of the energy recovery process for electricity
A	allocation factor between two life cycles	B	allocation factor of energy recovery processes
Q_{sin}	quality of the ingoing secondary material	E_D	emissions consumed from disposal of waste material at EoL
Q_{sout}	quality of the outgoing secondary material		

In order to better understand the parameters of the CFF, Figure 33 represents a diagram of two life cycles, LC1 and LC2, and some of the parameters.

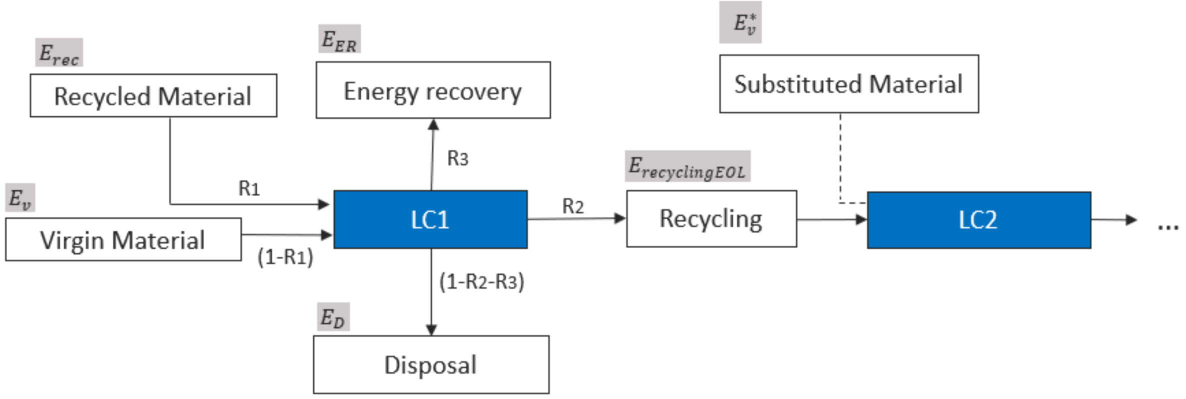

Figure 33- Schematic representation of two life cycles with CFF parameters

For LC1, it was assumed that all material was primary which means that there was no use of recycled material and therefore R_1 is 0. The parameters displayed in a grey box, in Figure 33, express emissions associated with a certain activity. E^*_v, for example, describes GHG emissions of virgin material that were substituted by recyclable materials.

This formula is not directly applicable in SimaPro, therefore in order to obtain results for these parameters of emissions, processes must be independently run in SimaPro and subsequently substituted in the formula.

As mentioned previously, this scenario was developed for the Netherlands where 20% of waste is sent to incineration and 80% is sent for recycling and therefore R_2 assumes the value of 0.8. For this work, energy recovery was not taken into account and for this reason the value of R_3 assumes the value of 0 and ($1-R_2-R_3$) is 0.2. Consequently, the energy part of the formula, represented in red, is excluded. Factor A, B and the ratios $\frac{Q_{sin}}{Q_p}$ and $\frac{Q_{sout}}{Q_p}$ are obtained from recommended default values. The values assumed for these parameters are shown in Appendix 5. The values considered for all the necessary parameters are shown in *Table 10*.

Table 10 - CFF formula parameters results

Parameter	**Value**	**Unit**
R1	0	-
R2	0.8	-
R3	0	-
E_v	18.6	kg CO_2 eq
E_{rec}	0	kg CO_2 eq
$E_{recyclingEOL}$	3.1	kg CO_2 eq
E^*_v	3.7	kg CO_2 eq
E_D	6.9	kg CO_2 eq
A	0.5	-
B	0	-
$\frac{Q_{sin}}{Q_p}$	0.9	-
$\frac{Q_{sout}}{Q_p}$	0.9	-

Besides the results given by the formula it was also necessary to add impacts of transport and energy required for manufacturing, obtained in SimaPro, to the final result as CFF does not consider them. The values of these contributions are described in Appendix 5. By substituting all the parameters in *equation 1* and adding the contributions of transport and energy, the CFF result of GWP for the HDPE drum can be obtained.

The final results attained from this approach are displayed in Table 11.

Table 11 - Results of total GWP impact and comparison between End of life methods

	Initial Allocation	**CFF**
Global Warming Potential (kg CO_2 eq) impact of HDPE drum 200 L	30.3	24.6

The main difference between the CFF approach and the approach showed in section 5.4.2 comes from assumptions on where to apply benefits and burdens of recycling. CFF method shows slightly lower impact on GWP than the method used throughout this project. This result was to be expected as in the method showed in 5.4.2 only burdens of recycling were considered, unlike the CFF method that also consider the benefits.

If results were not of the same order of magnitude, it would be required to perform a more comprehensive study and test a larger number of end-of-life approaches. In this case the GWP results from both allocations are similar. Therefore, because of this and due to the fact that the initial allocation is easier to apply, it was concluded that the use of the initial allocation is feasible.

CHAPTER 8

Conclusions

One of the goals of this dissertation was to improve understanding of the current packaging situation, highlighting concerns and requirements of each region where Corbion facilities are located, namely the Netherlands, Spain, Brazil, Thailand and the USA, as well as providing a detailed cradle-to-grave description of the different packaging alternatives and associated environmental impacts.

The assessment of the current situation, carried out by gathering and processing information obtained from several departments across all regions, evidence that sustainability is seen as a key factor for development, but also that its degree of importance varies between country. This variation is mainly due to cultural values, environmental awareness and also to local government regulations. The main priority of customers is still quality and price but there has been some concern regarding more sustainable packaging alternatives. This applies especially to bigger companies which have a large public exposure and are increasingly put under pressure to adopt sustainable behaviors. In the Netherlands for example, sustainability weights around 20% of the decision when choosing packaging from suppliers. Customers, in Spain and in the USA, have shown interest in biobased and recycled options. Although in Brazil sustainability is not at the core of decision, Procurement has demonstrated interest in studying different packaging alternatives. Thailand, on the other hand, is the region that takes less notice to the environmental performance of its packaging and discussions with packaging suppliers focus mainly on quality and price.

Taking the whole life cycle of each packaging into account, results demonstrate that, for all five regions, the main contributor for environmental impact is the material production stage (HDPE, Steel and Wood). This indicates that recommendations for reducing environmental performances of packaging should be mainly focused on this life stage. Comparison between production of the three main materials, HDPE, steel and wood, indicate that wood contributes significantly more to the REU and Land Use impact category while HDPE and steel contribute more for GWP, NREU and Water Use. The end-of-life stage shows different degrees of contribution depending on the region as disposal methods are significantly different between them. The transportation stage is, for all categories, the stage that shows less contribution for impact.

The packaging options that were studied vary with region given the fact that different geographies have distinct products and requirements. For the USA, paper options were considered, contrarily to other regions. Due to the low impact of the production of paper, results evidence that all paper options perform better than the other possible choices. The shift between smaller packaging into larger options should be carried out whenever possible as it often contributes to the decrease of GHG emissions.

The study of different scenarios demonstrated that there is significant potential for reduction of environmental impact. Following one of the major trends in packaging regarding material reduction, results show that decreasing plastic content, either by decreasing wall thickness of drums or by removing plastic lining of corrugated boxes, translates into savings. Additionally, replacing virgin material for recycled material exhibits improvements on its environmental performance. Using 50% of recycled HDPE in the 200 L Drum and in the IBC with plastic pallet show a reduction of 41% and 18% in GWP, respectively. On the other hand, the usage of 100% recycled steel in the IBC with steel pallet translates to 44% of savings in GHG emissions. Furthermore, the usage of bio-based plastic enables the shift away from fossil resources and consequently decreases GWP impact. These are some examples of possible changes that could be implemented in order to improve the environmental performance of the packaging used by Corbion.

8.1 Future Work

There are several topics that were not considered in this work and that would be relevant to be addressed in the future.

One of them is the necessity to test the applicability of the proposed suggestions in order to conclude if they are viable. Although the scenarios that were studied promote a lower environmental impact their application needs to be further investigated. This need is related to physical properties of the products as well as interest and receptivity of customers or even factors in production line. The section of scenarios, in chapter 7, study possible improvements based on the main trends in the packaging industry. A possible next step would be to test some of the scenarios in the form of a pilot project. One possible example would be to carry out a pilot experiment with biobased packaging, preferably a smaller option like pail or jerry can, in order to study its performance.

An interesting future project could be the development of a user-friendly app to share with customers that would include all the data presented in this work and would, therefore, allow them to be aware of the environmental impact of the different environmental categories for range of packaging alternatives. This would be an effective and fast way to help customers in their decision.

Improvements on data acquisition must also be taken into account. There are certain issues that should be addressed in order to obtain more accurate results. For instance, packaging production requirements should be discussed with each supplier. There is some uncertainty about the disposal methods that were considered, therefore disposal for each region should be better investigated near customers and local disposal facilities. This would help to gather more rigorous data that better corresponds to reality.

Another important future step would be to join external programs and initiatives that could allow the study of more impact categories. As previously discussed, littering associated with packaging, especially plastic packaging, is a major issue of this industry but it was not considered in this work.

In this study the most relevant packaging options were chosen. There were, however, some other alternatives that are currently being used in Corbion that were not assessed such as bulk trucks, fiber drums and carton IBC's. This was due either to lack of data from suppliers or from production inputs. Although its impacts were not quantified, they are interesting alternatives that should be investigated.

Bibliography

[1] United Nations -Department of Economical and Social Affairs, "World population Prospects: The 2017 Revision," 21 June 2017. [Online]. Available: https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html. [Accessed 13 June 2020].

[2] United Nations - Department of Economic and Social Affairs, "2018 Revision of World Urbanization Prospects," 16 May 2018. [Online]. Available: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. [Accessed 26 June 2020].

[3] Statista, "Global plastic production from 1950 to 2018," [Online]. Available: https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/. [Accessed 23 june 2020].

[4] National Geographic, "Planet or plastic?," 20 December 2018. [Online]. Available: https://www.nationalgeographic.com/news/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/. [Accessed 29 August 2020].

[5] Ellen Macarthur Foundation (2013), "Towards the Circular Economy - Economic and business rationale for an accelerated transition," [Online]. Available: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

[6] Kirchherr, J. et al. (2017), "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation & Recycling 127, 221-232,* https://doi.org/10.1016/j.resconrec.2017.09.005.

[7] Naudé, M. (2011), "Sustainable development Companies: theoretical dream or implementable reality?," *Corporate Ownership and Control, 8(4-3), 352-364,* vol. 8, no. 4, p. 361, http://dx.doi.org/10.22495/cocv8i4c3art4.

[8] European Environment Agency (2016), "Circular Economy in Europe, Developing the knowledge base," Publications Office of the European Union, Luxembourg, doi:10.2800/51444.

[9] Rizos,V., Tuokko, K., Behrens, A., (2017), "The circular Economy: A review of definitions, processes and impacts," CEPS Research Report NO. 2017/09.

[10] Corbion, "Sustainability - Life Cycle Assessment," [Online]. Available: http://www.corbion.com/about-corbion/sustainability. [Accessed 19 September 2020].

[11] World Economic Forum and Ellen Macarthur Foundation, (2016), "The New Plastics Economy. Rethinking the future of plastics," Available at: https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics.

[12] European Union, "Directive 2008/98/EC of the european parliament and of the council on waste and repealing certain directives," 2008. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098.

[13] ING Economics Department, (2019), "Plastic packaging in the food sector," Available at: https://think.ing.com/uploads/reports/ING_-_The_plastic_puzzle_-_December_2019_(003).pdf.

[14] Voulvoulis N., Kirkman,R., Giakoumis, T.,, Metivier, P., Kyle, C., and Midgley, V., (2020), "Examining Material Evidence. The carbon footprint," *Emperial College of London,* Available at: https://www.imperial.ac.uk/media/imperial-college/faculty-of-natural-sciences/centre-for-environmental-policy/public/Veolia-Plastic-Whitepaper.pdf.

[15] European Comission, "Circular Economy - Closing the loop: Clear targets and tools for better waste management," Available at: https://ec.europa.eu/commission/sites/beta-political/files/circular-economy-factsheet-waste-management_en.pdf.

[16] European Comission - Institute for Environment and Sustainability, (2012), "Product Environmental Footprint (PEF) Guide," Availabe at: https://ec.europa.eu/environment/archives/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf.

[17] International Organization for Standardization 14040 (2006), "Environmental Management - Life Cycle Assessment - Principles and Framework".

[18] Guinée, J. et al. (2010), "Life Cycle assessment: past, present and future," *Environ. Sci. Technol. 2011, 45, 90-96,* https://doi.org/10.1021/es101316v.

[19] International Council of Chemical Associations, "How to Know If and When it´s Time to Comission a Life Cycle Assessment: Executive guide," Available at: https://icca-chem.org/wp-content/uploads/2020/05/How-to-Know-If-and-When-Its-Time-to-Commission-a-Life-Cycle-Assessment.pdf.

[20] Forster,P.,Artaxo.,P., Berntsen, T., et al (2007), "Changes in Atmospheric Constituents and in Radiative Forcing.," *Chapter 2,* Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf.

[21] Frischknecht, R., at al, (2007), "Implementation of Life Cycle Impact Assessment Methods".*Swiss Centre for Life Cycle Inventories - Ecoinvent report No.3.*

[22] Brentrup, F., Kusters, J., Lammel, J. et al, "Life Cycle Impact Assessment of land use based on the hemeroby concept," *Int J LCA 7,339 (2002),* htto://dx.doi.oro/10.1065/Ica2002.07.087.

[23] Frischknecht, R., Jungbluth, N., (2007) , "Overview and Methodology".*Swiss Centre for Life Cycle Inventories.*

[24] European Comission - JRC Tecnhical Reports, (2019), "Suggestions for updating the Product Environmental Footprint (PEF) method," Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC115959/jrc115959_pef_method-online.pdf.

[25] M. Huijbregts, S. Hellweg, R. Frischknecht, H. Hendriks, K. Hungerbuhler and J. Hendriks, "Cumulative Energy Demand as predictor for the Environmental Burden of Commodity Production," *Environ. Sci. Technol. 2010,44,6,2189-2196,* https://doi.org/10.1021/es902870s.

[26] Golsteijn, L., (2012), "ReCiPe," Available at: https://pre-sustainability.com/articles/recipe/. [Online]. [Accessed 4 September 2020].

[27] PRé, "Consider Your Audience when doing impact assessment," March 2014. [Online]. Available: https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/. [Accessed 15 August 2020].

[28] European Comission, "Environment: a new medals table for waste management (2012)," Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_12_888.

[29] Afvalfonds Verpakkingen, "Afvalfonds Verpakkingen - Packaging waste fund," [Online]. Available: https://afvalfondsverpakkingen.nl/en/packaging-waste-fund. [Accessed 14 April 2020].

[30] WWF (2019), "Solucionar a Poluição: Transparência e Responsabilização," WWF - Fundo Mundial para a natureza, Available at: http://promo.wwf.org.br/solucionar-a-poluicao-plastica-transparencia-e-responsabilizacao.

[31] Chiemchaisri, C., Juanga, J.P., Visvanathan, C., "Municipal Solid Waste Management in Thailand and disposal emission inventory (2008)," *Environmental Monitoring and Assessment 135, 13-20,* https://doi.org/10.1007/s10661-007-9707-1.

[32] United States Environmental Protection Agency, "Facts and figures about Materials, Waste and Recycling: Paper and paperboard Material," [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/paper-and-paperboard-material-specific-data. [Accessed 16 May 2020].

[33] Materials Processing Institue, "Eletric Steelmaking - The new paradigm for UK steel manufacture," *The Steel Industry Series (2016),* Available at: https://www.mpiuk.com/downloads/industry-papers/SI-Series-Paper-02-Electric-Steelmaking-The-New-Paradigm-for-UK-Steel-Manufacture.pdf.

[34] Deviatkin, I.,Khan,M., Ernst, E., Horrttanainen,M., "Wooden and Plastic Pallets: A review of Life Cycle Assessment (LCA) Studies," *Sustainability 2019, 11, 5750,* Available at: doi:10.3390/su11205750.

[35] C. Nicholas P and R. Paul E, "Handbook of Pollution Prevention and Cleaner Production," in *Chapter 6 - Sources of air emissions from pulp and paper mills*, Available at: DOI: 10.1016/B978-0-08-096446-1.10006-1, pp. 179-259.

[36] Z. Chengliang, X. Tong, F. Hualiang and C. Shaohua, "Greenhouse Gas Emissions from Landfills: Review and bibliometric analysis," *Sustainability 2019, 11(8), 2282,* Available at: https://doi.org/10.3390/su11082282.

[37] European Bioplastic (2020), "Mechanical Recycling," Available at: https://docs.european-bioplastics.org/publications/bp/EUBP_BP_Mechanical_recycling.pdf.

[38] Toniolo, S., et al., "Allocation Strategies in comparitive life cycle assessment for recycling: Considerations from case studies".*Resources, Concervation and Recycling 117 (2017) 249-261.*

[39] PRé Sustainability, "Effective LCA with Simapro," [Online]. Available: Available at: https://simapro.com/business/life-cycle-assessments/. [Accessed 17 June 2020].

[40] Tua, C., Biganzoli, L., Grosso,M, Rigamonti, L., , "Life Cycle Assessment of Reusable Plastic Crates (RCPs), 2019," *Resources 2019,8,110,* doi:10.3390/resources8020110.

[41] Ernst & Young Global Limited (2015), "Life Cycle Assessment of Newly Manufactured and Reconditioned Industrial Packaging," Available at: http://thatdruminternational.com/wp-content/uploads/2016/10/TDI-FJS-Sustainability-RIPA-Life-Cycle-Analysis-Final-Oct-2015.pdf.

[42] FPE - Flexible Packaging Eurpope, "Updated study confirms flexible packaging plays a key role in prevention of packaging waste and mitigation of global warming," 2020. [Online]. Available: https://packaging360.in/news/updated-study-confirms-flexible-packaging-plays-a-key-role-in-prevention-of. [Accessed 15 July 2020].

[43] Mauser Packaging Solutions, "Mauser Infinity Series - Giving plastic packaging materials a new life," Available at: https://redefiningsustainability.com/products/.

[44] F. Harvey, "The guardian - Steel Industry," 23 May 2019. [Online]. Available: https://www.theguardian.com/business/2019/may/23/recycling-steel-could-give-lifeline-to-the-industry-report-says. [Accessed 10 July 2020].

[45] Broadbent, C., (2016), "Steel's recyclability: demonstrating the benefits of recycling steel achieve a circular economy," *LCA of Metals and Metal Products: Products, Theory, Method of Practice,* DOI: 10.1007/s11367-016-1081-1.

[46] W. Association, "Energy used in the steel industry," *(2018),* Available at: https://www.worldsteel.org/en/dam/jcr:f07b864c-908e-4229-9f92-669f1c3abf4c/fact_energy_2019.pdf.

[47] U. E. I. Administration, "Recycling is the primary energy efficiency technology for aluminum and steel manufacturing," Available at: https://www.eia.gov/todayinenergy/detail.php?id=16211.

[48] Siracusa, V., Blanco, I., "Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications".*2020.*

[49] Braskem, "I'm green polyethylene - Innovation and Differentiation for your Product," [Online]. Available: http://plasticoverde.braskem.com.br/site.aspx/Im-greenTM-Polyethylene. [Accessed 29 July 2020].

[50] Braskem, "I'm Green PE Life Cycle Assessment," Available at: https://www.ivecopack.de/images/pdf/Life-Cycle-Assessment-v02.pdf.

[51] Stephens, M., Meyers, F., in *Manufacturing Facilities. Design and Material Handling*, Pearson Education, 2013, p. 243.

[52] San Diego Steel Pallets, "San Diego Steel Pallets," [Online]. Available: https://sandiegosteelpallets.com/why-steel-pallets/#:~:text=The%20biggest%20return%20on%20investment,some%20repairs%20along%20the%20way.. [Accessed 4 June 2020].

[53] Biganzoli, L., Rigamonti, L., Grosso, M.,(2018), "Intermediate bulk container re-use in the circular economy: an LCA evaluation," *Procedia CIRP, Volume 69, pages 827-832,* Available at: https://doi.org/10.1016/j.procir.2017.11.010.

[54] Ernst & Young, (2014), "Life Cycle Assessment of Newly Manufactured and Reconditioned Industrial Packaging," Available at:https://www.reusablepackaging.org/wp-content/uploads/Life-Cycle-Analysis-Report-2014.pdf.

[55] Procurement Department at Corbion, "Procurement and Sustainability PowerPoint".

[56] PreciseEthiopia, "Profile on the Production of Woven PP Bags," Available at: https://preciseethiopia.com/download/publication/business_opportunities/Profile%20on%20the%20Production%20of%20Woven%20PP%20Bags.pdf.

[57] Tua, C., Biganzoli,L., Grosso, M., Rigamonti, L. , "Life Cycle Assessment of Reusable Plastic Crates (RPCs), 2019," *Resources 2019, 8, 110 ,* doi:10.3390/resources8020110.

[58] Biganzoli, L., Rigamonti, L., Grosso, M., (2018), "Intermediate Bulk Containers re-use in the circular economy : an LCA evaluation," *Procedia CIRP, Volume 69, pages 827 - 832,* Available at: https://doi.org/10.1016/j.procir.2017.11.010.

[59] Pires, A., Martinho, G., (2019), "Waste hierarchy index for circularity for circular economy waste management," *MARE; Waste Management 95, 298-305,* https://doi.org/10.1016/j.wasman.2019.06.014.

[60] McKinsey and Company, (2020), "The drive toward sustainability packaging - beyond the quick wins," Available at: https://www.mckinsey.com/industries/paper-forest-products-and-packaging/our-insights/the-drive-toward-sustainability-in-packaging-beyond-the-quick-wins.

[61] Global Recycling - The Magazine for Business Opportunities & International markets, "Better Waste Management to Combat Climate Change," [Online]. Available: https://global-recycling.info/archives/2941. [Accessed 23 April 2020].

[62] United Nations - Environment Programme (2019), "The new plastic economy gloabal commitment - 2019 progress report," Available at: https://www.newplasticseconomy.org/assets/doc/Global-Commitment-2019-Progress-Report.pdf.

[63] Center for Strategy and Competitiveness Stockholm School of Economics (2017), "European Cluster Observatory: Priority Sector Report: Circular Economy".

[64] New Plastics Economy and Ellen Macarthur Foundation (2017), "The New Plastics Economy: Rethinking the Future of Plastic and catalysing action," Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/NPEC-Hybrid_English_22-11-17_Digital.pdf.

Appendix

Appendix 1 - Diagrams

The following diagram depicted in Figure - 1 represents the inputs and outputs that are necessary to build the model for the IBC in SimaPro. The IBC with plastic pallet was the chosen packaging option to showcase inputs and outputs of the model, all the other packaging won't be described as they follow a similar model. The inputs are the amount of production materials, energy required for manufacturing and transport distances. It is also necessary to give information to SimaPro about output regarding the disposal methods that are considered.

a) IBC

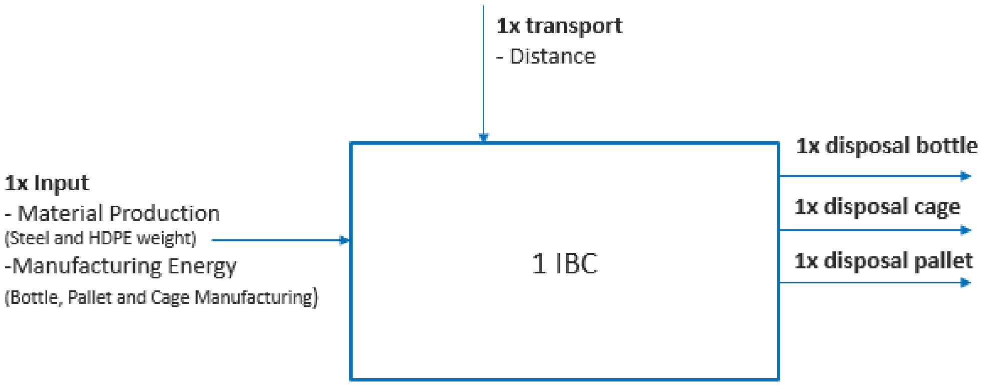

Figure- 1 IBC with plastic pallet diagram model

b) Reconditioned IBC

For the reconditioned IBC slightly different inputs are used. It is considered that the IBC can be reconditioned five times before it is sent to disposal, as described in Figure-2. The five steps shown include the cleaning of the bottle as well as transportation of pallet and cage to allow its reuse. After the fifth use, the IBC cannot be used any longer and so it is sent to disposal.

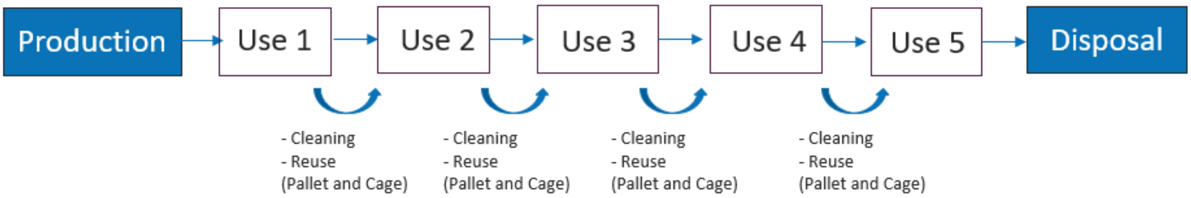

Figure- 2 Reconditioned of the five life cycles of a reconditioned IBC.

The model built in SimaPro representing all the required inputs and output to get impacts of the reconditioned IBC is presented in Figure – 3.

It is similar to the normal IBC but it has additional inputs such as the “reconditioned input” which accounts for the water, cleaning solution and energy required to perform the reconditioning between each use and the Cage and Pallet “Reuse” which account for the extra transport of these elements between uses.

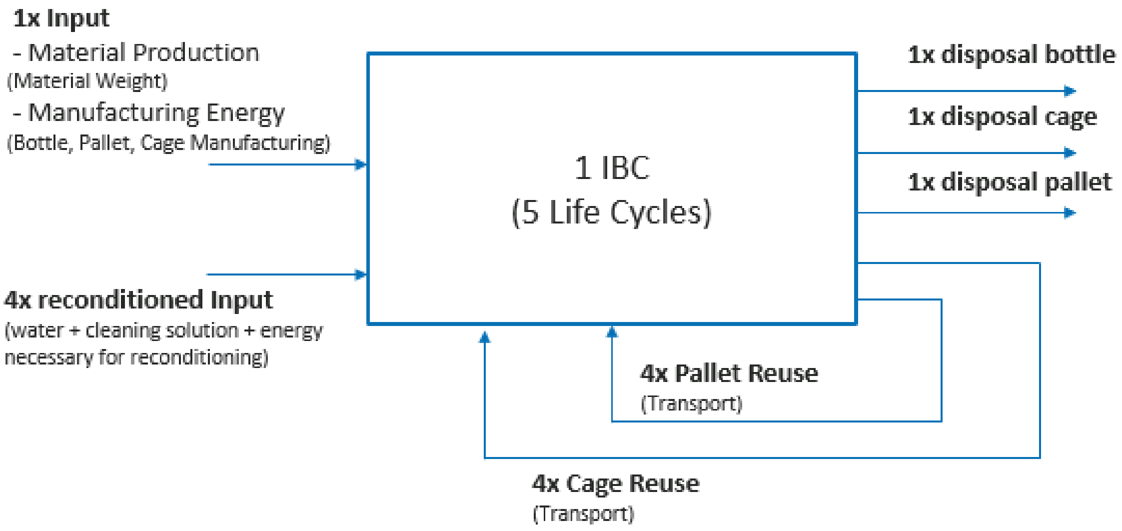

Figure- 3 Reconditioned IBC Diagram Model

Appendix 2 – Packaging Models

Due to the assumption made that similar packaging has the same weight across regions, it will only be shown the most relevant inputs for each region. As a packaging example, the model for the IBC and the drum option are described for the Netherlands, the model for the Jerry Can for Spain and for the Super Sack, Paper Bag, Carton Box and Pail for the USA.

The database that comes in SimaPro has an extensive number of processes that describe all the activities required within the life cycle of a product. A process is a set of interacting activities that transform inputs to outputs. From the used database two types of process can be selected, either Unit Processes or System Processes. When using Unit processes, it is possible to easily adapt a given dataset to make it more specific to the study as it gives access to the user to control all the flows that are considered. Therefore, if the user wished to exchange any activity or any value this is possible while using unit processes.

The processes that were chosen for the IBC model are referred through different acronyms under "Process name" in Table- 1 and Table -2. For example, the U seen in the "process name" means Unit Process.

An allocation, in SimaPro, is the distribution of the input and output flows to the products of a certain process and it is required when there is the need to assign contributions of environmental impact to multiple products and co-products. The default system model for allocation contained in the database used in this work is called " Allocation at the point of substitution" (APOS) and it is used in the majority of the processes.

Also relevant for the process is the data classification between either "transformation process" or "market process". The former process contains all the inputs for making a product whereas the latter dataset represents an average consumption mix of a certain product and considers one or more inputs from different transforming activities. Therefore, if a certain product can be produced in distinct ways, the "market process" will automatically take into consideration the average used of each process by the industry and generate one single process. The "transformation process" is the product itself and contains all the inputs for making a product. For this work, due to the considerable uncertainty regarding production methods used in the industry, it is beneficial to use "market" processes.

For transport processes calculations EURO6 it is the most updated dataset and it represents emissions standards.

Another detail worth noting is that all processes are geographically delimited, this is generally made per country, but it may also be Global ({GLO}), European ({EUR}) or Rest of the world ({RoW}) (not Europe).

a) Netherlands

IBCs are essentially constituted from three main parts: steel cage, an HDPE bottle and the pallet. The pallet can be made out of HDPE, Steel or Wood and three different IBCs are modelled.

The inputs presented in Table-1 are the common inputs to the three IBC options, the HDPE bottle and the steel cage. The zinc coat is necessary in steel (steel cage and steel pallet) in order to protect it from corrosion. Electricity and Heat inputs correspond to the energy required for packaging manufacturing.

Table - 1 Data Input for IBCs in the Netherlands

		Plastic Bottle	**Steel Cage**	**Zinc coat**	**Electricity**	**Heat**
IBC	**Process Name**	Polyethylene, high density, granulate {GLO}| market for | APOS, U	Steel, low-alloyed {GLO}| market for | APOS, U	Zinc coat, pieces {GLO}| market for | APOS, U	Electricity, medium voltage {NL}| market for | APOS, U	Heat, district or industrial, natural gas {RER}| market group for | APOS, U
	Unit	kg	kg	m^2	kWh	MJ
	Values	16	22	1.32 (for cage) + 2.4 (for steel pallet)	28.1	0.34
	Source	[53]	[53]	[53]	[54]	[54]

As to transport calculations a distinction has to be made regarding the nature of pallet material. Transport inputs are weight, which is different for different materials, and travelling distances. The unit for this category is kgkm.

For the data inputs presented in Tables-1 and 2, the following assumptions were made.

- Electricity Production and the Heat input for the Steel pallet IBC is 28.1 kWh [54] and 0.34 MJ, respectively. The same values were assumed for the Plastic pallet IBC and the Wood pallet IBC.

- Regarding transportation, as shown in Table-1, the units of the process for wood pallet is given per piece but for transport calculation it is required to know the weight of this pallet. Therefore, it was assumed that the wood pallet weighted 25 kg, which is the average European standard. [34]

Table - 2 Data Input for IBCs divided by pallet

	IBC with Plastic Pallet		**IBC with Steel Pallet**		**IBC with Wood Pallet**	
	HDPE Pallet	**Transport**	**Steel Pallet**	**Transport**	**Wood Pallet**	**Transport**
Process Name	Polyethylene, high density, granulate {GLO}| market for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U	Steel, low-alloyed {GLO}| market for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U	EUR-flat pallet {GLO}| market for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
Unit	kg	kgkm	kg	kgkm	piece	kgkm
Values	16	14592	22	14848	1	16128
Source	[53]	Assumed + Data provided by Corbion	[53]	Assumed + Data provided by Corbion	None	Assumed + Data provided by Corbion

Data input for the HDPE drum presented in Table -3 is also considered only for the Netherlands. The model for other regions is the same except for “Electricity” process which is specific for each region.

Table - 3 Input data for HDPE Drum in the Netherlands

		Plastic	**Electricity**	**Heat**	**Transport**
HDPE Drum 200 L	**Process Name**	Polyethylene, high density, granulate {GLO}| market for | APOS, U	Electricity, medium voltage {NL}| market for | APOS, U	Heat, district or industrial, natural gas {RER}| market group for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kWh	MJ	kgkm
	Values	8.5	7.5	1.16	14 590
	Sources	[55]	[55]	[54]	Assumed + Data provided by Corbion

Within the transportation section, for sequential patch were considered as represented by the arrow in Figure -4.

Figure- 4 Diagram of transport trips necessary during one life cycle

For transportation calculations, the distances between Corbion and the Supplier (number 2 in Figure – 4) are depicted in Table – 4 for the IBCs and Drums option in the Netherlands. All other paths represented by number 1,3 and for 4 are assumed to be 100 km each.

Table – 4 Transportation distances between the Supplier and Corbion in the Netherlands

Transportation	**Distance (km)**	**Source**
Drums	30	Data provided by Corbion
IBCs	156	

b) SPAIN

For Spain the general data input data is shown in Table -5 for the Jerry Can only.

The inputs necessary to model the Jerry can are presented in Table -5. Similarly, to the IBCs and drums, for the Jerry cans, it is necessary to know the amounts of materials, in this case polyethylene, Electricity and Heat required for the manufacturing of this packaging and finally transport data.

Here, all values were calculated based on the HDPE Drum of 200 L. A proportion relationship based on volume was considered between the 200 L drum from Spain and the 20 L jerry can.

Table – 5 Input data for Jerry Can 20l in Spain

		Plastic (kg)	**Electricity**	**Heat**	**Transport**
Jerry can 20 L	**Process Name**	Polyethylene, high density, granulate {GLO}| market for | APOS, U	Electricity, medium voltage {ES}| market for | APOS, U	Heat, district or industrial, natural gas {RER}| market group for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kWh	MJ	kgkm
	Values	1.1	0.75	0.116	220
	Sources	[55]	[55]	[54]	Assumed

Table- 6 shows data regarding transportation distances between the Supplier and Corbion in Spain. All other transport distances were considered to be 100 km each.

Table – 6 Transportation distances between the Supplier and Corbion in Spain

Transportation	**Distance (km)**	**Source**
Drums	45	Data provided by Corbion
IBCs	130	

c) USA

In the case of the USA, the data required to model the Super Sack, Paper bag, Carton Box and the 5 gallon Pail options are presented in Tables -7 to -10.

For the other pails of 3.5 gallons and 2 gallons a proportional relationship based on volume regarding weight, electricity and heat was applied. As to transport modelling, the paths from production site to Corbion, Corbion to customer and customer to disposal were considered. In some cases, no data was available for heat supply.

Table – 7 – Input data for Super Sack in the US

		Polypropylene	Electricity	Transport
Super Sack – FIBC	**Process Name**	Polypropylene, granulate {GLO}| market for | APOS, U	Electricity, medium voltage {US}| market group for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kWh	kgkm
	Values	2.473	0.217	300 km * 2.473 kg = 742
	Sources	Corbion Average	[56]	Assumed

Table – 8 Input data for Paper Bag in the US

		Paper	Plastic Liner	Electricity	Transportation
Paper bag	**Process Name**	Kraft paper, bleached {GLO}| market for | APOS, U	Packaging film, low density polyethylene {RoW}| production | APOS, U	Electricity, medium voltage {US}| market group for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kg	kWh	kgkm
	Values	0.237	0.019	0.0194	78.1
	Sources	Corbion Average	Data provided by Corbion	Value taken from SimaPro process "Paper, bag and sack, unbleached kraft, average production, at mill/kg/RNA"	Assumed

Table – 9 Input data for Carton Box USA

		Carton Box	**Plastic Liner**	**Electricity**	**Heat**	**Transportation**
Carton Box	**Process Name**	Corrugated board box {RoW} | production| APOS, U	Packaging film, low density polyethylene {RoW}| production | APOS, U	Electricity, medium voltage {US}| market group for | APOS, U	Heat, district or industrial, natural gas {CH}| market for heat, district, natural gas| APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kg	kWh	MJ	kgkm
	Values	0.5	0.103	0.324	1.773	173.5
	Sources	Data provided by Corbion	Data provided by Corbion	Value taken from SimaPro process: “Carton board box, with offset printing {CH} | carton board box production service, with offset printing | APOS, U	Value taken from SimaPro process: “Carton board box, with offset printing {CH} | carton board box production service, with offset printing | APOS, U	Assumed

Table – 10 Input data for Pail 5 gallon USA

		Plastic	**Electricity**	**Heat**	**Transport**
Pail 5 gallon	**Process Name**	Polyethylene, high density, granulate {GLO}| market for | APOS, U	Electricity, medium voltage {US}| market group for | APOS, U	Heat, district or industrial, natural gas {GLO}| market group for | APOS, U	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
	Unit	kg	kWh	MJ	kgkm
	Values	0.940	0.713	0.11	300 km * 0.940 kg = 282
	Sources	Supplier Info	Assumed the same for 200 L PE drum (Proportional relationship based on volume) [54]	Assumed the same for 200 L PE drum (Proportional relationship based on volume) [54]	Distance of 100 km was assumed for each trip.

Appendix 3 – Disposal

As previously emphasized disposal is an important stage of any packaging end-of-life analysis. So, besides all the described inputs, it is also necessary to introduce data regarding the output flows of the model. The inputs used in this work concerning the waster treatments (output data) are described in Table – 11. Due to lack of data, it was assumed that the energy necessary for wood recycling is the same of that of plastic packaging.

Table – 11 Disposal data – Disposal processes used from Simapro per region

Region	Disposal Method	Process Name
Netherlands	Plastic Recycling	Plastic recycling_NL (Electricity+Transport)
	Steel Recycling	Steel Recycling_NL
	Plastic Incineration	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, municipal incineration | APOS, U
	Wood Recycling	Wood recycling_NL (Assuming electricity=plastic recycling)+transport
	Wood Incineration	Waste wood, untreated {RoW}| treatment of waste wood, untreated, municipal incineration | APOS, U
Spain	Plastic Recycling	Plastic recycling_Spain+transport
	Steel Recycling	Steel Recycling_Spain
	Wood recycling	Wood recycling_Spain (Assuming electricity=plastic recycling)+ transport
Brazil	Steel Recycling	Steel Recycling_BR
	Plastic Disposal	Waste plastic, mixture {BR}| market for waste plastic, mixture | APOS, U
	Wood Disposal	Waste wood, untreated {BR}| market for waste wood, untreated | APOS, U
Thailand	Steel recycling	Steel Recycling_TH
	Open Dump of Plastic	Waste polyethylene {GLO}| treatment of waste polyethylene, open dump, dry infiltration class (100mm) | APOS, U
	Sanitary landfill of Plastic	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | APOS, U
USA	Steel Recycling	Steel Recycling_USA
	Sanitary Landfill of Plastic (Polyethylene and Polypropylene)	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | APOS, U
	Sanitary Landfill of Wood	Waste wood, untreated {RoW}| treatment of, sanitary landfill | APOS, U
	Sanitary Landfill of Paperboard	Waste paperboard {RoW}| treatment of, sanitary landfill | APOS, U
	Paper Recycling	Paper recycling_US
	Sanitary Landfill of Paper (paper bag)	Waste graphical paper {RoW}| treatment of, sanitary landfill | APOS, U

There are a few disposal methods which are missing in the database used in this work and therefore need to be described. Tables -12 to 15 show the details of these disposal methods. These disposal methods are common for different regions, but this fact only influences the “Electricity” process.

Table - 12 Disposal data - Paper recycling process

Paper Recycling	**Electricity**
Process Name	Electricity Medium Voltage (for each region)
Value	0.6
Unit	kWh
Source	Assumption : same value as PE (waste treatment recycling) from DataBase Ecoinvent 3

Table - **13** Disposal data - Steel Recycling Process

Steel Recycling	Electricity	Transportation
Process Name	Electricity Medium Voltage (for each region)	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
Value	0.0475	100 km * packaging weight
Unit	kWh	kgkm
Source	[53] Approximate value as it only considers crushing of steel	Assumed

Table - 14 Disposal Data Wood Recycling Process

Wood Recycling	**Electricity**	**Transportation**
Process Name	Electricity Medium Voltage (for each region)	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
Value	0.6	100 * packaging weight
Unit	kWh	kgkm
Source	Assumption: same value as “PE waste treatment recycling” from DataBase Ecoinvent 3	Assumed

Table - 15 Disposal Data Plastic Recycling Process

Plastic Recycling	**Electricity**	**Transportation**
Process Name	Electricity Medium Voltage (for each region)	Transport, freight, lorry 16-32 metric ton, euro6 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U
Value	0.6	100 km * packaging weight
Unit	kWh	kgkm
Source	“PE waste treatment recycling” Database Ecoinvent 3.5	Assumed

Appendix 4 - Reconditioning

The reconditioning step requires the removal of residues between life cycles/reuses using a cleaning solution and water. The cleaning solution, is made from three different solutions [57] whose composition is described in Table -16.

Table-16 Proportions of compounds in the cleaning solution

Solution	Component	Proportion (%)
1	Sodium Hydroxide	30
	Deionized water	70
2	Sodium Hypochlorite	14
	Deionized Water	86
3	Citric Acid	10
	Lactic Acid	5
	Deionized Water	85

The following table, Table 17, describes the additional inputs in SimaPro to model the reconditioning process.

Table - 17 Data for the Reconditioning Process

	Process Name	Unit	Value	Source
Water	Water, deionised, from tap water, at user {Europe without Switzerland}| market for water, deionised, from tap water, at user | APOS, U	kg	84.4	[57] , [58]
Electricity	Electricity, medium voltage {NL}| market for | APOS, U	kWh	14.04	[54]
Heat	Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | APOS, U	MJ	46.10	[54]
Neutralising agent	Neutralising agent, sodium hydroxide-equivalent {GLO}| sodium hydroxide to generic market for neutralising agent | APOS, U	kg	19.6	[57]
Citric Acid	Citric acid {RER}| production | APOS, U	kg	0.175	[57]
Lactic Acid	Lactic acid {RER}| production | APOS, U	kg	0.0875	[57]
Sodium Hypochlorite	Sodium hypochlorite/RER	kg	0.735	[57]

In the literature it is reported [58] that for the recondition process the water requirement is 70m^3 for 1 IBC. For the amount of the cleaning solution that is used, no information was found. Only the proportions of the compounds of the solution were found. Therefore, it was assumed that 35 kg of cleaning solution per IBC, half of the amount necessary of water would be required for reconditioning.

Appendix 5 – Circular Footprint Formula

The Circular Footprint Formula was presented in section 7.8 of this document. The assumed values for each parameter are as follow.

a) Added Contributions

As explained in section 7.8 of this document, the CFF does not take into account contributions of transport nor energy required for the packaging manufacturing. Due to this fact, these contributions were calculated separately in SimaPro and added to the result given by the CFF formula. These results are presented in Table- 18.

Table - 18 Results of GWP of Transport and Manufacturing Energy for 200 L Drum HDPE in the Netherlands

Life Stages	GWP (kg CO_2 eq)
Transport	4.57
Energy (Packaging Manufacturing)	0.18

b) A factor

The A factor allocates burdens and credits from recycling and virgin material production between two life cycles and it tries to reflect the reality of the current market. In PEF studies the *A* factor values should be between 0.2 and 0.8 to make sure that this factor always accounts for recycling. If *A*=1, it means that it was considered that all credits were given to the recycled content. On the other hand if *A* = 0 it means that all recycling credits were considered at the end of life. For this study, there are recommended default A values considering specific materials. For the Drums, the HDPE is the only material and its default A value is present in the following table.

Table - 19 Default value of A factor for HDPE

Material	A Factor Value	Source
HDPE	0.5	Data provided by Corbion (Default values)

c) B factor

The B factor is used as an allocation factor for energy recovery processes. In PEF studies the B value should be equal to 0.

d) Q ratios

The Q ratios, $\frac{Q_{sin}}{Q_p}$ and $\frac{Q_{sout}}{Q_p}$ take into account the quality of the ingoing and outgoing recycled material. The quantification of these quality ration is based on economic aspects, i.e. price ratio of secondary materials compared to primary. For this study, both ratios were obtained from default values provided by Corbion. Since in section 7.8 of this document, the analyzed packaging was an HDPE drum, HDPE was the selected material. The default values used for different materials are shown in table-20

Table - 20 Default values of Q ratios for packaging material

Material	Default value (Qsin/Qp)	Default value (Qsout/Qp)	Source
Steel	1	1	Data provided by Corbion (Default values)
HDPE	**0.9**	**0.9**	
LDPE film	0.75	0.75	