Politecnico di Milano

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING
Renewables and Environmental Sustainability– Energy Engineering

LIFE CYCLE IMPACTS OF ASEPTIC CARTON USED FOR DRINKING WATER DELIVERY

Supervisors
Prof. Mario Grosso
Prof. Lucia Rigamonti

Co-Supervisor
Ing. Camilla Tua

Candidate
LAVINIA PIA PERSICO - 892156

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Acknowledgements

Sommario

Le prestazioni ambientali di una bottiglia d’acqua in materiale poliaccoppiato da 0,5 litri sono state analizzate con l’approccio del ciclo di vita (Life Cycle Assessment – LCA). La bottiglia è composta da un contenitore in cartone asettico (comprensivo di uno strato il polietilene e uno in alluminio) e da una chiusura in polipropilene. L'ambito geografico dello studio è quello del Nord Italia e i dati raccolti sono relativi agli anni 2017-2019. Il sistema è descritto principalmente con dati raccolti per precedenti analisi e adottati in questa a causa della difficoltà di reperimento di dati relativi al cartone asettico. Acqua Smeraldina è l’unica azienda italiana che distribuisce acqua in bottiglie da 0.5 L in cartone asettico. I dati primari sull’imballaggio primario e secondario (massa e tipo di materiale) sono stati raccolti acquistando dei campioni di Tetra Pak Prism consegnati in scatole di cartone da Acqua Smeraldina. La valutazione è basata su 14 categorie d’impatto suggerite dall’Environmental Footprint Life Cycle Impact Assessment Method, versione 2.0 (Fazio et al., 2018). L’analisi include la produzione dell’imballaggio primario e secondario, il trasporto, la distribuzione e il fine vita. Dai risultati, il contributo più impattante è dato dal ciclo vita del contenitore in cartone asettico, specialmente per la produzione e il trasporto della carta e dei fogli di alluminio. Sono stati analizzati tre scenari per il fine vita del contenitore in cartone asettico: raccolta con il rifiuto residuo e avvio a incenerimento, raccolta con la carta e riciclo in cartiera convenzionale, raccolta con la carta e riciclo in cartiera dedicata. Quest’ultimo risulta il miglior scenario; il riciclo in cartiera convenzionale il peggiore. Da un’analisi di sensitività sui consumi di acqua ed energia di una cartiera dedicata, la cartiera specializzata rimarrebbe il miglior scenario anche se il consumo di acqua fosse 30 volte più elevato di quello di una cartiera convenzionale. Quindi il risultato dell’analisi di sensibilità dipende solo dal consumo di energia. A riguardo, la cartiera dedicata rimane il miglior scenario fino a consumi di energia pari a quattro volte quelli di una cartiera convenzionale. Se il consumo di energia della cartiera dedicata fosse uguale a cinque volte o più di quello di una cartiera convenzionale, l’incenerimento sarebbe la miglior soluzione. Nella seconda parte della tesi, la bottiglia in cartone asettico è confrontata con la bottiglia in PET. Per la distribuzione nazione, la bottiglia in PET risulta la migliore soluzione.

Abstract

A Life Cycle Assessment (LCA) approach was used to study the environmental performance of 0.5-liter aseptic carton bottle for drinking water distribution. The bottle is formed by an aseptic carton container and a PP closure. The geographical scope of the study is Northern Italy and collected data are related to the years 2017-2019. The foreground system was mainly described with data collected for previous analyses and adopted here due to lack of data relative to aseptic carton. Primary data about the primary and secondary packages (mass and material) were gathered by collecting samples of 0.5 L Tetra Pak Prisms and cartonboard boxes from Acqua Smeraldina. The assessment is based on 14 impact categories from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018). The analysis includes the manufacturing of the primary and secondary packaging, as well as its transportation, distribution and end-of-life. As a result, the most important burden to the total impact of the system is given by the life cycle of the aseptic carton container, especially for the production and transportation of paperboard and aluminum. Three scenarios for end-of-life of aseptic carton container are analysed: collection with the residual waste followed by incineration, collection with paper and recycling in a conventional paper mill, collection with paper and recycling in a dedicated paper mill. The latter results the best scenario, the recycling in conventional paper mill the worst. By applying a sensitivity analysis on the water and energy consumption, it was discovered that the dedicated paper mill would remain the best scenario even if the request of water of a dedicated paper mill is 30 times higher than a conventional paper mill. So, the results of sensitivity analysis depend only on the request of energy. Dedicated paper mill is the best scenario even in case of a-four times increase of energy consumption of a conventional paper mill. If the energy consumption increases by five times or more, the best scenario for end-of-life of aseptic carton container becomes the incineration together with the residual waste.

Finally, the aseptic carton bottle is compared with the PET bottle. For water distribution in Italy, PET bottle results the best option.

Extended Abstract

In recent years, packaging has become one of the key factors through which manufacturers can show to the customers an orientation towards sustainability and environmental protection.

Our case study is related to the society A.L.B. S.p.A. (Tempio Pausania, Sassari), which commercializes the “Smeraldina” brand bottled water, where an aseptic carton bottle is available among its products.

Aseptic carton for beverage packaging is widespread for fruit juices, wine and milk, while mineral water is generally packed in PET or glass bottles. It is called “aseptic” because it includes an aluminium foil for long-term conservation. It is composed by 75% of paperboard, 20% of LDPE foil and 5% of aluminium thin foil. Paperboard provides stability, strength and smoothness for the printing surface, polyethylene is used as a barrier against water and bacteria and as an adhesive layer, while aluminium foil protects against oxygen and light to maintain the nutritional value and flavour of the food/beverage even at room temperature.

According to Protocollo d’Intesa Tetra Pak – Comieco, three different collection methods are identified (in addition to the collection together with the residual waste):

- together with paper, without any downstream separation, followed by recycling in conventional paper mills;
- together with paper with downstream separation in specific platforms, followed by recycling in dedicated paper mills;
- together with multi-material collection (plastic, glass and cans), followed by recycling in dedicated paper mills.

In Italy 27 conventional paper mills accept beverage carton up to a maximum of 3% in weight of the input waste. Paper waste normally requires a few minutes for the fibre pulping,

while aseptic carton waste is humid-resistant due to the presence of LDPE and it would take 30-45 minutes to complete the process. So only a small part (30-40%) of the cellulosic fibre is effectively recovered. Moreover, the treatment of 1 kg of aseptic carton generates 1.5 kg of residues (not recovered paper + 100% Al and PE + absorbed water), increasing the costs of disposal.

Only two Italian paper mills are specialised in the recovery of aseptic carton waste: Cartiera SACI (Verona) and LUCART (Lucca). Thanks to a dedicated pulping process, they can separate paper from aluminium and plastic recovering up to 90% of the paper fibres. Plastic and aluminium remain intimately attached between each other, and they are used as a secondary raw material obtaining a new material called EcoAllene used in building, promotional and costume jewellery.

This thesis focuses on the distribution of water in the Horeca sector (e.g., restaurants and cafés) for the Northern Italian context and it has the following objectives:

- to assess the environmental performance associated to the distribution system of mineral water in a 0.5 litre aseptic carton container;
- to identify the contribution to the impacts of the main stages of the system (production of primary and secondary packages, bottling plant operations, bottles distribution, and packages end of life);
- to provide suggestions for modifying the system in order to improve its environmental performance at the large scale. This aspect is very important considering that the analysed way of distribution has been recently introduced in Italy by a single brand of mineral water;
- to make a comparison with the traditional PET bottles distribution system.

The distribution system is based on aseptic carton bottles formed by an aseptic carton container and a PP closure. The components of the bottle are manufactured in dedicated plants and then transported to the reference bottling facility. Here, the containers are filled with mineral water, capped, arranged in groups of 24 each one and finally placed in a cardboard box. Bottles are then transported by road from the bottling plant to a local distributor in the Northern Italy (300 km on the average), which delivers them to the final user. After the water consumption, bottle components and the cardboard boxes are discarded by the user in the municipal waste and collected and treated according to the urban waste management system in the Northern Italy.

The function of the analyzed system is to provide a certain volume of mineral water to the final user by 0.5-liter aseptic carton bottles and so the selected functional unit is *the delivery of 100 liters of mineral water (corresponding to 200 analyzed bottles)*.

The analysed system includes:

- the manufacturing of the primary and secondary packages and the relative transportation to the bottling plant;
- the operations at the bottling plant (filling, capping, and packing into boxes);
- the distribution of aseptic carton water bottles (transportation from the bottling plant to the local distributor and then to the final user);
- the end of life of the primary and secondary packages, i.e. collection and waste treatment in dedicated facilities.

The assessment is based on 14 impact categories from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018). The geographical scope of the study is the Northern Italy and collected data are related to the years 2017-2019. The foreground system is mainly described with primary data except for the bottling plant operations for which literature data were used.

The impact contribution analysis (figure 1) reveals that the life cycle of the aseptic carton container is the most important burden to the total impact of the system in all the impact categories. Depending on the category, this contribution ranges from 45% (freshwater ecotoxicity) to 97% (ozone depletion) and it is mainly associated to the production and transportation of the paper boards and aluminium foils. Another important stage in terms of impacts is the transportation of the bottles from the bottling plant to the local distributor (300 km on average). Its contribution is higher than 15% in eight impact categories and reaches a maximum contribution of 37% in the freshwater ecotoxicity indicator.

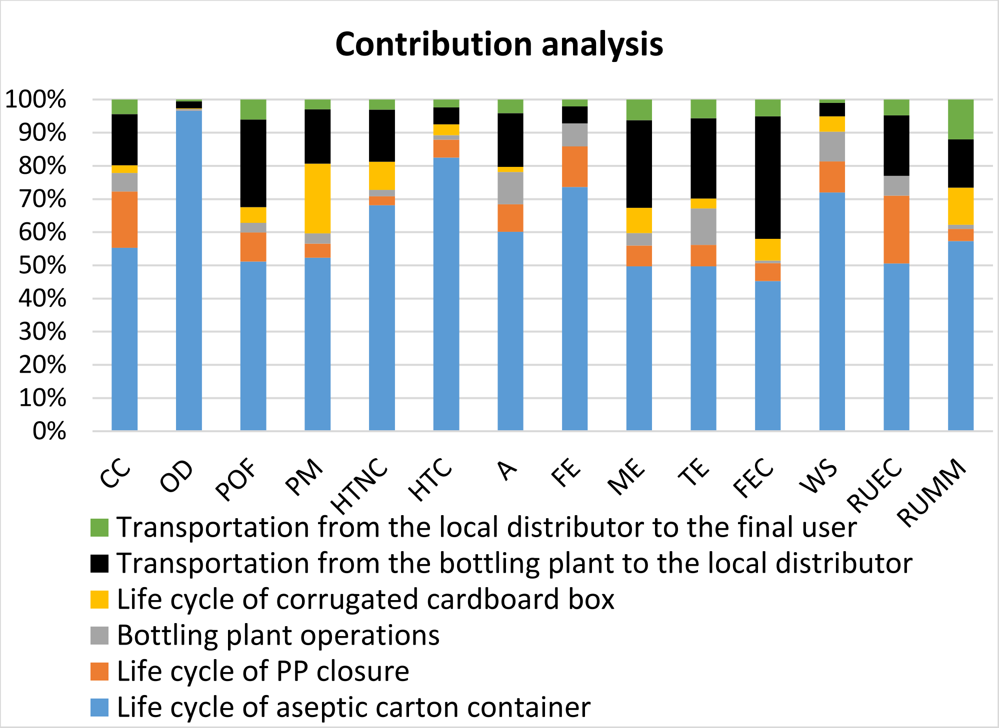

Figure 1. Percentage contribution of the different stages to the total impacts of the distribution system based on 0.5L Aseptic carton bottles (scenario related to the incineration of post-consumer containers).

Three scenarios for the end of life management of the aseptic carton container are analysed: treatment with the residual waste, treatment in a conventional paper mill and treatment in a dedicated paper mill specifically adapted for processing this type of containers. The latter results the best solution of waste management for 12 out of 14 categories (figure 2). On the contrary, the treatment in a conventional paper mill results the worst option in 8 out of 14 impact indicators. In general terms, we can conclude that the end of life of the aseptic carton container does not significantly influence the overall impacts of the water distribution system.

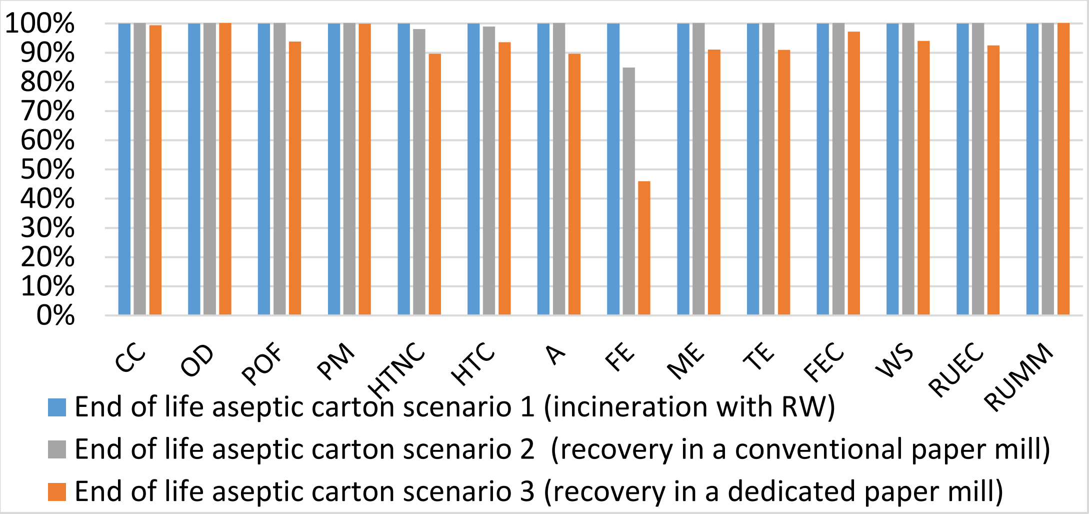

Figure 2. Comparison between the impacts associated to the different scenarios of aseptic carton waste management (1 kg). In the graph, the impact of Scenario 3 is put at 100%

However, it must be considered that for the analysis of the third scenario no data were available in the literature and neither dedicated paper mills nor Tetra Pak have provided us with any data because they are part of the company's know-how. So in a first tentative we only changed the percentage of recovered thermomechanical pulp (increased to 90%) and the distance between sorting plant and dedicated paper mill (increased from 100 to 200 km, since only two dedicated paper mills are available in Italy), keeping all other data constant with respect to the conventional paper mill. This lack of data is the starting point for the sensitivity analysis: energy and water consumption of a dedicated paper mill are analysed. As a result, dedicated paper mill remains the best scenario even if the request of water of a dedicated paper mill is 30 times higher than a conventional paper mill. So, the results of sensitivity analysis depend only on the request of energy. Dedicated paper mill is the best scenario up to four times increase of the request of energy. If the energy consumption is five times or more, the best scenario for end-of-life of aseptic carton container is the incineration. The second part of this study was focused on the comparison between one-way aseptic carton containers and one-way PET bottles, in order to evaluate which system has a better environmental performance. The environmental performance of PET bottles was evaluated in another work of the AWARE group, a master thesis in environmental engineering (Grisales, 2020). As end-of-life of aseptic carton containers, we consider the best one derived from the sensitivity analysis, that is the third analysed scenario: advanced paper mill. As shown in figure 3, for ten categories out of fourteen, the PET bottle results clearly better than the aseptic carton container. Specially, in the latter, the production and transportation of paper board and aluminium foils are particularly have a considerable impact. When increasing the distribution distance for both systems, PET and aseptic carton become more comparable, but considering the national distribution (up to 900 km) PET system will remain the best solution.

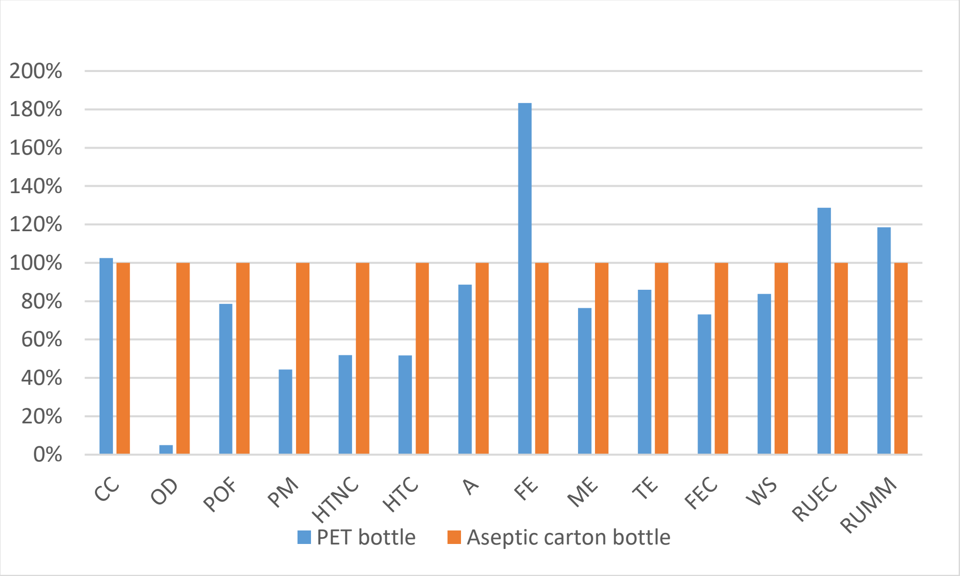

Figure 3. Comparison between PET bottle and aseptic carton bottle (scenario 3 as end-of-life of aseptic carton container) for each impact category. In the graph, the impact of aseptic carton bottle is put at 100%.

However, at the end of this analysis, it must be considered that the LCA method takes into account the environmental impact of the life cycle of the product concerned. LCA defines the best solution based on environmental performance, so it does not take into account important factors related to the choice of the best packaging such as the preservation of the drink. For example, PET, when exposed to the sun for a long time, releases hazardous substances into the water, while aseptic carton, thanks to its aluminum layer, preserves water from exposure to light and ensures better conservation.

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Chapter 1

Introduction and Scope of the Work

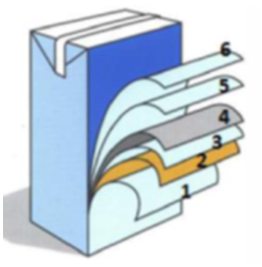
Bottled water consumption in Italy is amongst the highest at the European level and, in the biennium 2017-2018, it has set a record with a total consumption of around 13,400 million litres, corresponding to a per capita value of more than 220 litres annually. The major part of the consumed volume (82%) is distributed through PolyEthylene Terephthalate (PET) bottles (Bevitalia, 2019). In the recent years, packaging has become one of the key factors through which manufacturers can show to the customers an orientation towards sustainability and environmental protection. So, alternative containers (refillable glass bottles and aseptic carton bottles) have been promoted in the Italian context, with the claim of being more environmentally friendly. In particular, the society A.L.B. S.p.A. (Tempio Pausania, Sassari), which commercializes the Smeraldina brand bottled water, proposes an Aseptic carton bottle among its products (https://www.acquasmeraldina.it/cms/).

Considering the high consumption of bottled water in Italy, it is essential to evaluate the environmental performance associated with the new aseptic carton container as well as to understand whether, under particular conditions, the substitution of traditional PET bottles can allow for a reduction of the environmental impacts across the whole production, distribution and and-of-life management systems. To this aim, in this thesis the environmental impacts of the water distribution with aseptic carton bottles are calculated and a detailed contribution analysis is shown with suggestions for a future improvement of the system. A comparison with the traditional PET bottles distribution system is also reported. The environmental performance of this system was assessed in another research work of the AWARE group (Grisales, 2020). It is important to underline that the focus of the study is the consumption of mineral water in the Horeca sector (e.g., restaurants and cafés).

Chapter 2

Board Cartons Packaging for Liquids

Board cartons packaging for liquids, introduced by Ruben Rausing in 1951 for the cream in Sweden, are tetrahedron-shape packages mainly based on wood fibres and polyethylene. In case aseptic quality is needed, an additional aluminium layer is included. Cellulose is the main material, which provides stability, strength and smoothness for the printing surface. Polyethylene is used as a barrier against water and bacteria and as an adhesive layer, while aluminium foil protects against oxygen and light to maintain the nutritional value and flavour of the food/beverage at room temperature. The three raw materials are layered together by a lamination and coating process to form a six-layered packaging according to the characteristics reported in Figure 4.



Layer	Material	Grammage (g/m^2)	Function
1	LDPE	12-30	1) Protection against moisture 2) Protection of prints 3) Surface with a glossy look
2	Paperboard	225	1) Stiffness and stability to the packaging 2) Print surface for design and images
3	LDPE	15	Adhesive between paperboard and aluminium foil
4	Al foil	20	Barrier to oxygen, light and flavors
5	LDPE + EAA^1	8	Adhesive between aluminium foil and internal LDPE layer
6	LDPE and LLDPE	20	Sealing and protecting the product

^{1} EAA = Ethylene Acrylic Acid

Figure 4. Typical structure of an aseptic carton laminate and function of each layer (Grumezescu and Butu, 2019).

Nowadays, beverage aseptic carton is a very common packaging for food and beverage products. Its widespread diffusion is due to the following reasons:

- aseptic packaging allows for extended shelf life, whilst keeping the product fresh and maintaining its nutritional value (consumers can store the product for a longer time without refrigeration and no preservatives);
- carton packs are lightweight, unbreakable, and easy to open;
- because of their parallelepiped shape they can be stacked together closely with minimal wasted space (a trailer of filled carton packs carries around 95% content with just 5% of space taken by the packaging). This aspect makes cartons more efficient to transport than circular section containers like plastic or glass bottles, resulting in fewer trucks on the road, less fuel used and less space needed to store the products (Skoda, 2019).

According to different recent market researches, the global aseptic packaging market amounts to about USD 30-45 billion in the last years and it is expected to keep on growing at a Compound Annual Growth Rate (CAGR) of 7-10% (Table 1). In particular, in the European context, the production was equal to USD 9.7 billion in the year 2015 and the market of this sector is expected to grow by 9.9% up to 2024 (Global Market Insights Inc., 2016).

Table 1. Current value of the global aseptic packaging market and forecast-growing rate in the future years according to different market researches.

Source	**Actual market USD**	**Compound Annual Growth Rate (CAGR)**	**Reference website**
MarketsandMarkets TM INC.	39.6 billion in 2017	10.89% (2017-2022)	https://www.marketsandmarkets.com/PressReleases/aseptic-packaging.asp
DATA BRIDGE	31.6 billion in 2017	9.9% (2018- 2025)	https://www.databridgemarketresearch.com/reports/global-aseptic-packaging-market
ALL THE RESEARCH	41.2 billion in 2018	9.6% (2018-2026)	https://www.alltheresearch.com/report/258/aseptic-packaging-market
Mondor Intelligence	46.1 billion in 2019	6.65% (2020-2025)	https://www.mordorintelligence.com/industry-reports/aseptic-packaging-market

According to data of The Istituto Nazionale Imballaggi (2018), from the year 2015 the production in Italy has stabilised at around 140,000 t/year with a turnover of about EUR 470 million. The data of national production seems to be in accordance with Tetra Pak Italia (Tüv Italia Blog, 2017), which reported the distribution of 4.5 billion containers (about 100,000 t) in the year 2013, 3/4 of which destined to the internal market. Aseptic carton containers are mainly used in the beverage sector. For example, in the market of fruit juices about 50% of the sold volume (360 Ml) is packed in bricks (Bevitalia, 2019), and 34% in the wine sector (LargoConsumo, 2014). For water, to our knowledge only one company in Italy uses Tetra Pak containers, i.e. "Acqua Smeraldina". Regarding the management of the end of life, the amount of aseptic carton packages separately collected and sent to recycling in Italy is gradually increasing, from 22.700 t in 2014 to 26.000 t in 2018. Concerning the recycling rate (i.e., the amount of material really recovered in the recycling facility), the only indication derives from Tetra Pak, whose global recycling rate is about 25% (Tetra Pak, 2019).

2.1 Collection Methods

In addition to collection with residual waste and then sent to incinerator, three different collection methods are currently in place in Italy for aseptic cartons, but unfortunately very limited quantitative information is publicly available about their end-of-life management:

- Joint with separate collection of paper without any downstream separation. The material is directly delivered to a conventional paper mill. In this case, starting from a threshold of 0.35% by weight, the cardboard packaging consortium (Comieco) pays the paper mill a specific recycling contribution to offset the additional costs arising from the presence of aseptic carton;
- Joint with separate collection of paper with downstream separation in a platform. In case the partner in charge of separate collection also takes care of the separation, Comieco pays, in addition to the costs of separate collection, a fee for the sorting and the separated fraction goes to a dedicated paper mill. If the dedicated paper mill makes the separation, Comieco will negotiate with the dedicated paper mill the costs for sorting and recycling;

- Together with multi-material packaging (plastic and/or glass and/or cans), followed by recycling in specialised paper mills;

Once collected and sorted, the containers are pressed into bales and sent to the paper mills for their recycling.

In 2002 a study was published that evaluated the separate collection of aseptic carton together with the organic waste, when none of the above options are practicable and composting plants are available. This recovery scheme was proposed in the framework of an experimentation of AIMAG in collaboration with Tetra Pak. The cellulosic fraction, which is the one that accounts for the highest weight fraction, might be properly recovered in a composting process, which would also allow to separate and recycle aluminium and polyethylene downstream the process. The principle is the following: the cellulosic matrix is attacked by the microorganisms involved in the composting process, and eventually degraded to obtain compost. A possible scheme could therefore be the following: pre-treatment with hydro-mechanical system for the delamination of paper, aluminium and polyethylene components; mixing with other organic fractions deriving from separate collection; composting; recovery of non-biodegradable fractions, such as wood, iron, polyethylene and aluminium (the latter deriving from cartons); final product consisting of compost to be used, after quality selection, as soil conditioner.

The result of this study was that 30% of aseptic carton in the input sample was found in the over-sieve fraction (not degraded) and 70% of aseptic carton was degraded.

However, this study has remained only an experiment without any follow-up, and the collection methods currently adopted are the three above mentioned.

2.1.1 Recycling in Conventional Paper Mills

According to Tetra Pak, in Italy there are about 27 paper mills not dedicated in the processing of beverage cartons (which in any case receive this material together with waste paper). Conventional paper mill can accept aseptic cartons for a maximum of 3% of the input waste. According to the information provided by Comieco (Casti et Al, 2015), aseptic cartons collected together with paper account for 1.7% in weight of the total. This value might seem negligible, but it is a big problem for conventional paper mills, since they can only recover a small percentage of cellulose and the rest is waste that has to be disposed of at their own expenses. This is because when the aseptic carton arrives at the paper mill it is difficult to separate the paper from the plastic or metal layers. The separation takes place in the pulper thanks to the water that macerates the paper, but the aseptic carton is water-resistant on purpose. As a consequence, only a fraction (30-40%) of the cellulosic fiber can be extracted from the cartons, the rest becoming waste. The treatment of 1 kg of aseptic carton waste generates 1.5 kg of residues to be disposed (not recovered paper + 100% Al and PE + large amount of absorbed water about 50% of residues). This waste can be treated through energy recovery in waste-to-energy plants.

2.1.2 Recycling in Dedicated Paper Mills

In Italy only two paper mills are specifically designed to process aseptic cartons:

- SACI paper mill in Verona is able to dismember the cartons in all their components and obtain “Cartafrutta” and “Cartalatte”. Cartafrutta is Havana-coloured and comes from the recycling of aseptic containers used for long conservation made of paper, polyethylene and aluminium. Cartalatte is white and is obtained from fresh milk containers without the aluminium layer;
- Lucart paper mill in Lucca, through the Natural project born from the collaboration between Lucart and Tetra Pak, obtains Fiberpack (a raw material which allows to produce paper products with superior performance) from cellulose fibres. From aluminium and polyethylene, they obtain AL.PE (material used to produce dispensing systems for paper, pallets for the transport of goods and other commonly used products).

The dedicated paper mills follow a particular process, whose technical specifications are not disclosed, being part of the know-how of the companies. The sole information that I could collect come from talking with some experts.

Generally, the process is composed by:

- a batch pulper at high density, which has the purpose of separating the fibrous material into elemental fibres;

- Filtration system for aluminium and polyethylene and other waste: a cone with which, thanks to centrifugal force, paper remains on the walls and waste falls;
- Storage;
- Coarse and fine screening system: series of perforated tanks with variable diameter. Thanks to the difference in specific weight and consistency of the mixture in each tank, residues are removed and pulp is recovered. Between one tank and another there is a storage phase;
- The total waste is then washed with a large excess of water and the mixed aluminium-plastic stream is collected.

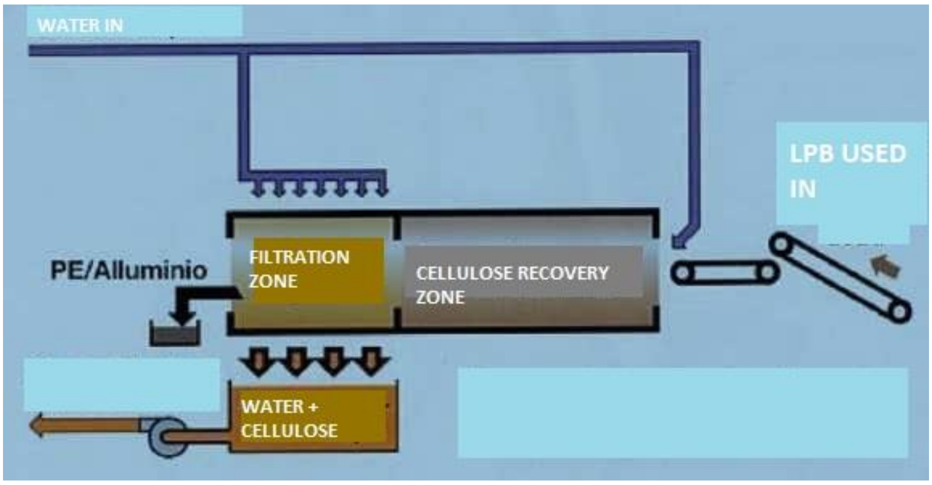


Figure 5. Typical process of dedicated paper mill

Thanks to this process, dedicated paper mills can recover up to 90% of the paper carton of aseptic cartons.

2.2 Recovery of the Residues from Aseptic Cartons Processing

In recent years, some companies have tried to use such residue as a secondary raw material. The first plant dedicated to its recycling was built in the city of Alessandria by the company Ecoplasteam, which has developed an innovative treatment process thanks to which it is possible to transform waste into a new raw material, called EcoAllene.

The Alessandria area was chosen for its strategic position, between two paper mills carrying Aseptic carton waste trucks.

Its innovation consists in the treatment of waste without separating the two components (plastic film + aluminium film), keeping them aggregated in the production process. This reduces the costs of recycling allowing an important competitiveness of the finished products with plastic.

2.2.1 EcoAllene

EcoAllene is obtained by applying the following processes:

- A deep wash of the waste for a cleaning and recovery of any residual fibres (cellulose) that will be put back on the market to re-enter its production cycle or destined to self-production of energy;
- A shredding of the product to allow the workability of the waste and the "management" of the size of the aluminium present in the material to be processed, reducing it to just under 1 mm^2, thus also allowing the dosage of the same in the final recipe according to the market / application of destination;
- Agglomeration to homogenize the material and prepare it for the addition of additives/mixing and extrusion phase;
- An extrusion where, by using heat, additives and a plasticization process, the formulations are prepared (base material + filler and/or additive) intended for the market in general or finalized, with "tailor-made" recipe, to the specific customer.

The material finally obtained is called EcoAllene, composed by polyethylene and a small percentage of aluminium. It has plastic properties, it is printable and can be used in building, promotional and costume jewellery. EcoAllene comes in the form of granules, sold in large containers of one ton each, and from which multiple products can be obtained.

As shown in figure 6, EcoAllene can be employed in various ways:

- production of soles and heels for footwear;
- production of brooms and household items;
- clocks and vases;
- toys.

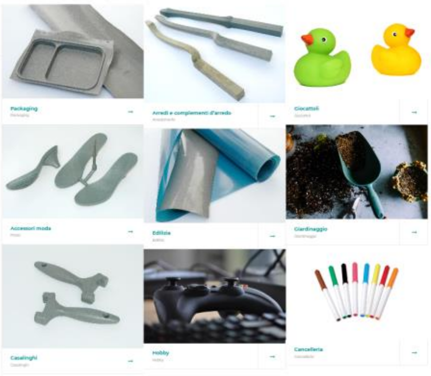


Figure 6. Employments of EcoAllene

Chapter 3

The Life Cycle Assessment (LCA) Methodology

3.1 History of LCA

LCA was born at the beginning of the 1960s, when environmental degradation and the increased limited access to resources became a global concern. In that period, collaboration between universities and manufacturers resulted in what was then called a Resource and Environmental Profile Analysis (REPA) or Ecobalance. These terms were used until the 1990s, when the term LCA became a norm (Hauschild et al., 2017). The early methods were essentiality a material and energy accounting. As inventory results got more complex, these were translated into environmental impact potentials.

During the 1990s, the impact assessment evolved with the goal of avoiding burden shifting. In 1992, the Institute of Environmental Sciences at Leiden University (the Netherlands) published the first impact assessment methodology, the CML92, which sets midpoint impact categories. Meanwhile, the Swedish EPS method focused on damages caused to ecosystems and human health was released. This approach was then followed by the Eco-indicator 99, which had a more science-based methodology to damage modelling (Vigon et al., 1993). During the following decades, numerous assessments were done, but results differed because of variations in data standards and quality. By 2003 this situation was improved with the release of the first ecoinvent database (version 1.01), which provided life cycle inventory data for energy, materials, waste management, transports, agricultural products, and processes (ESU-services, 2019), and covered all industrial sectors, giving consistent data standards and quality. Moreover, as the complexity of the models required enlarged, around

1990s, the first versions of software were released, such as SimaPro and GaBi, designed to deal with this type of data.

In 1993, a process of standardization, carried out by the International Organization of Standardization (ISO), began because there was not a proper methodology to carry out LCA studies and as a consequence, different analyses on the same product could give opposite results. Over the next seven years four standards were released, addressing the principles and framework (ISO 14040), the goal and scope definition (ISO 14041), the life cycle assessment (ISO 14042) and the life cycle interpretation (ISO 14043). In 2006, the latter three standards were compiled in the ISO 14044 standards detailing the requirements and guidelines.

Thereafter, in the mid-2000s, the European Commission initiated a process to develop an International Life Cycle Data System (ILCD) with a database of life cycle inventory data as well as a series of methodological guidelines with the objective of ensuring more consistent and reproducible results (European Commission, 2010). Afterwards, in 2012, the EU Commission launched the Product Environmental Footprint (PEF) (EC-JRC, 2012) and Organizational Environmental Footprint (OEF) Guidelines as abbreviated and revised versions of the ILCD guidelines targeting different categories of products or services to be applied by companies and organizations reporting on their environmental performance (Zampori & Pant, 2019).

In parallel various improvements have been done regarding the database, resulting in more accurate information. In 2019, the sixth iteration of ecoinvent database version 3.6 was released. This database contains more than 2,200 new and 2,500 updated datasets related to agriculture, building and construction material, chemicals, electricity, fishing, metal, refineries, textile, tourisms, transport, waste treatment and recycling, and water supply. As a result, the database now includes 4700 products and has expanded its geographical coverage to numerous countries previously not covered, such as Brazil, Colombia, Ghana, India, Perú and South Africa (ESU-services, 2019). The ecoinvent 3.5 database was deeply consulted for this work.

3.2 LCA Structure

The life cycle assessment methodology is based on four separated but interrelated parts which include: (1) goal and scope definition; (2) identification and quantification of main input and output flows in the different life cycle stages (Life Cycle Inventory, LCI); (3) quantitative characterization and assessment of the consequences on the environment (Life Cycle Impact Assessment, LCIA); (4) evaluation and interpretation of the results (Vigon et al., 1993). The four phases should not be kept separated (see Figure 7.) but should be considered as a part of an iterative process.

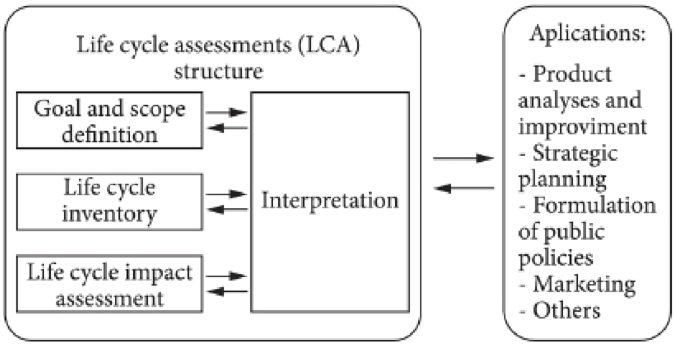


Figure 7. Stages of Life Cycle Assessment Methodology (Image from: ISO, 2006).

3.2.1 PHASE I: Goal and Scope Definition

The goal and scope definition identifies two distinct stages, the goal definition and the scope definition. The goal definition involves the statement of the following items: the intended application, the reason for carrying out the study, the intended audience, and whether the results are intended to be used in public comparative assertions.

On the other hand, in the scope definition the following items shall be clearly defined: the product system to be studied, its functionality and the consequent functional unit, the system boundary, the LCIA methodology and types of analysed impacts, and the data quality requirements.

The system boundary determines which unit processes are included in the analysis, and this selection must be consistent with the goal of the study. A complete LCA should include the entire life cycle (from cradle to grave or from cradle to cradle in case of recycling), but sometimes some phases are excluded. The omission of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusion of the study and it shall be clearly stated.

The functional unit quantifies the identified function(s) of the system. The functional unit shall be measurable and clearly defined, as one of the main purposes of a functional unit is to provide a reference to which the input and output data and the results are normalized. Moreover, if a comparison between different systems is required, it shall be done on the basis of the same function(s), quantified by the same functional unit in the form of their reference flow.

3.2.2 PHASE II: Life Cycle Inventory Analysis

The second phase of the LCA study consists in the construction of a model of the reality that shall represent as accurate as possible all the exchanges among the single processes of the analysed system. It is defined by the ISO 14040 as "*the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product through its life cycle*". The input and output data (i.e. energy inputs, raw material inputs, ancillary inputs, products, co-products, waste, emissions to air, water and soil) shall be referenced to the functional unit.

The final result of this stage is an environmental inventory that includes the amounts of material and energy consumption/production, of direct emissions into air, water and soil, and of waste.

The process of conducting an inventory analysis is iterative, as during the collection of data it is learned more about the system and as a consequence new data requirements or limitations may be identified. Data can be distinguished among primary data (deriving from direct surveys), secondary data (obtained from literature, such as databases and other studies), and tertiary data (from estimated and average values). Whenever possible, the study should be based on primary data.

3.2.3 PHASE III: Life Cycle Impact Assessment (LCIA)

The third phase of LCA aims at understanding and evaluating the magnitude and significance of the potential environmental impacts for the analysed product system/service throughout its life cycle. This process involves associating inventory data from phase II with specific environmental impact categories and category indicators, thereby attempting to understand the relative impacts.

The LCIA phase shall include: (1) selection of impact categories, category indicators and characterization models; (2) assignment of LCI results to the selected impact categories (classification); (3) calculation of category indicator results (characterization).

Selection of the impact categories, category indicators and characterization models shall reflect a comprehensive set of environmental issues related to the studied product system and shall take into account the goal and scope previously defined.

The subsequent classification stage implies the assignment of the inventory results to the selected environmental impacts, represented by the established environmental impact categories. Thereafter, the value of each category indicator can be calculated. This phase involves the conversion of the LCI results (using characterization factors) to common units and the aggregation of the converted results within the same impact category.

In addition, the LCIA includes three optional stages: normalization, grouping, and weighting. The normalization is the calculation of the magnitude of the category indicator results relative to some reference information, this with the objective of a better understanding of the relative magnitude for each indicator. The grouping is the assignment of impact categories into one or more sets as predefined in the goal and scope definition, and it may involve sorting and/or ranking. Lastly, weighting is the process of converting indicator results of different impact categories by using numerical factors based on valuechoices, with the aim of obtaining a final result represented by a single index, which defines the global environmental impact caused by the examined activity. These last three steps were not performed in this study.

3.2.4 PHASE IV: Life Cycle Interpretation

This stage includes the identification of the significant issues in the LCA study, an evaluation that considers completeness, sensitivity and consistency checks, and main conclusions, limitations, and recommendations.

Based on the previously obtained results of the LCI and LCIA phases, it is possible to identify the significant issues, in accordance with the goal and scope definition (e.g., most relevant life cycle stages in terms of contribution to the impact). Furthermore, with the objective of establishing confidence and reliability of the LCA results, a check of completeness, sensitivity and consistency should be performed. Lastly main conclusions, limitations and recommendations must be drawn. Recommendations shall be based on the final conclusions of the study and shall reflect a logical and reasonable consequence of the conclusions.

3.3 Limitations of LCA

The very core of an LCA study is to analyse the complete life cycle of a product, but this can be achieved only simplifying other aspects. Firstly, this methodology cannot address localized impacts and as a consequence does not provide a full-fledged local risk assessment study. The same is true for the time aspect, as the LCA is developed with a steady-state approach rather than a dynamic one.

Furthermore, LCA methodology focuses on physical characteristics related to the industrial activities and other economic processes,but does not include market mechanisms or secondary effects on technological development.

Moreover, the LCA focuses on the environmental aspects of the products or services, but does not take into account other features of the products such as their economic or social characteristics. The environmental impacts are described as “potential impacts”, because they are not specified in time and space and are related to an often arbitrarily defined functional unit (Guinée, 2002).

Finally, there is a limitation related to the data availability, as information is generally available on the standardized databases at the level of building blocks, such as electricity production, rather than for the individual constituting processes themselves.

Chapter 4

LCA of the Mineral Water Distribution System Based on Aseptic Carton Bottles

4.1 Previous LCAs on the Topic

In the existing literature, various studies have been carried out to assess which packaging material shows the lowest environmental burdens associated to its manufacturing, distribution, and end of life. Within the beverage sector, focus of this research, several studies have compared different single serving packages such as PET bottles, HDPE bottles, single use glass containers (CSU), lightweight single use glass bottles (LSU), refillable glass bottles (RFG) and aseptic carton bottles, in terms of LCA (e.g. Xie et al, 2011; Bertolini et al, 2013; Cleary, 2013). In four out of six studies analysed, aseptic carton shows the lowest overall environmental impacts. Table 2 reports some detailed information about the most relevant previous LCA studies.

Table 2. Summary of the previous literature studies related to LCA comparison between aseptic carton and other types of packaging for beverage distribution.

Literature source	Geographical context and type of beverage	Compared packages	Functional unit	System boundary	Scenario with the lowest impact	Characterization method and analysed impact categories	Main conclusion of the study
Xie et al., 2011	China, Milk packaging	Pa-Pe-Al; PET	1000 L of milk: -1000 Pa-Pe-Al packages of 1 L each -5000 PET packages of 200 mL each.	Manufacturing from raw materials, transportation, manufacture of the packaging, final disposal. Use stage is not included.	PET	Eco-Indicator 99 -human health -ecosystem quality -depletion of resources	-the results show clearly that the composite packaging has a slightly higher environmental impact than the plastic one. -if resource saving is the primary governmental goal, the composite packaging would be the better choice, while the plastic packaging would be the better choice for ecosystem protection
Bertolini et al., 2013	Italy. ESL (extended shelf life) milk packaging	multilayer carton; PET; HDPE	1 L of milk	Extraction of raw material, resin production, containers formation, production of cap, label and secondary packaging, transport of the packaged products,	Multi-layer carton	CML2001 -Global warming potential (GWP100) -photochemical ozone creation potential (POCP) - stratospheric ozone depletion potential (ODP)	-the multilayer carton is the most environmental friendly solution for almost all the impact categories considered and its environment impacts are on average more than 30% lower than both PET and HDPE.

				materials end of life. The environmental impact of beverage production has not been evaluated as also the storage of the packaged product in the retail store. Sterilizing, drying, filling and capping activities remain out of the system boundaries.		-human toxicity potential (HTP) -acidification potential (AP) -eutrophication potential (EP)	-Comparing PET and HDPE, PET has a lower impact in EP, GWP100, HTP and ODP, while HDPE turns out to be less impactful in AP and POCP.
Cleary, 2013	Toronto, wine and spirit packages	For wine: single use glass container [CSU], lightweight single use glass bottle [LSU], refillable glass bottle [RFG], PET bottle, aseptic carton [AC] For spirit: CSU, LSU, RFG, PET	1 L of wine 750 ml of spirit	extraction of the raw materials required for each container and the secondary packaging; transportation of the raw materials to processing facilities; raw material processing; transportation of the processed materials to the container manufacturer; manufacture of the container; transportation of the container to the packager; transportation of the container from the	RFG, AC	ReCiPe v1.02 -ecosystem diversity -human health -resource availability	The refillable glass bottle and aseptic carton have the lowest potential net environmental impacts, responsible for up to an 87% reduction in endpoint level impacts relative to the CSU glass bottle.

				packaging facility to retail outlets, recycling or disposal of the waste packaging materials and the avoided burdens associated with material recycling.			
Consorzio Universitario di Ricerca Applicata, Università degli Studi di Padova, 2005	Europe, Fresh and ESL (extended shelf life) milk packaging	PET and Tetra Top for fresh milk and HDPE and Tetra Prisma Aseptic for ESL milk	1 L of fresh milk and 1 L of ESL milk for each type of packaging	Production, packaging, primary distribution and end-of -life	Tetra Top for fresh milk Tetra Prisma Aseptic for ESL milk	Characterization method not specified. -energy analysis -water consumption -solid waste -greenhouse effect -acidification -eutrophication -photochemical oxidant formation -depletion of non-renewable resources	PET and HDPE have a similar behaviour, and Tetra Top and Tetra Prisma Aseptic also have a similar behaviour, except for the waste category (contribution of the aluminium extraction phase).
Ferrara and De Feo, 2020	Italy, wine packaging	Single-use glass bottle, bag-in-box, refillable glass bottle and multilayer PET bottle	3 L for each type of packaging	All the life cycle phases of the wine packaging systems were included in the system boundaries (except the wine bottling phase excluded due to lack of reliable data).	bag-in-box	ReCiPe 2016 H -ecosystem diversity -human health -resource availability	The single use glass bottle was the worst packaging alternative, followed by the multilayer PET bottle. The bag-in-box packaging system was the eco-friendliest alternative, with an impact from three to five times lower than single use glass bottles for the different

							impact categories considered. The aseptic carton was the second best packaging alternative after the bag-in-box, with only slightly higher impacts.
Meneses et al., 2012	Spain, milk packaging	Aseptic carton, HDPE and PET	1 L for each type of packaging	the impact of the milk production itself, and the transport of the packaged product were not included.	Aseptic carton	-global warming potential -acidification potential	Aseptic cartons present the lowest environmental impacts for all the indicators and disposal scenarios while the impact of both types of plastic packaging (HDPE and PET) is similar.

4.2 Goal Definition of the Study

The main objectives of the study are:

- to assess the environmental performance associated to the distribution system of mineral water in a 0.5 litre aseptic carton container for the Horeca sector;
- to identify the contribution to the impacts of the main stages of the system (production of primary and secondary packages, bottling plant operations, bottles distribution, and packages end of life);
- to provide suggestions for modifying the system in order to improve its environmental performance at the large scale. This aspect is very important considering that the analysed way of distribution has been recently introduced in Italy by a single brand of mineral water;
- to make a comparison with the traditional PET bottles distribution system (see Chapter 6).

4.3 Scope Definition

4.3.1 Description of The Aseptic Carton Distribution System for Mineral Water

The description of the system is based on the experience of Acqua Smeraldina, the only Italian brand of mineral water commercialized also in an aseptic carton container. The 0.5 litre packaging was launched on the market in the year 2011 and it is called Tetra Pak Prism. Table 3 reports its main characteristics (material and average mass) according to collected primary data.

Table 3. Main characteristics of the packaging under study. The mass of the components was derived by weighting of some samples of Smeraldina Tetra Pak Prism. Images is taken from: https://www.acquasmeraldina.it/cms/

Components of bottle	Material	Mass (g/item)
Container	Aseptic carton	21.5
Closure	Polypropylene	3.5

In the analysed water distribution system (Figure 8), the components of the bottle are manufactured in dedicated plants and then transported to the reference bottling facility. Here, the containers are filled with mineral water, capped, arranged in groups of 24 each one and finally placed in a cardboard box. Bottles are then transported by road from the bottling plant to a local distributor in the Northern Italy, which delivers them to the final user. After the water consumption, bottle components and the cardboard boxes are discarded by the user in the municipal waste and collected and treated according to the urban waste management system in the Northern Italy.

4.3.2 Functional Unit

The function of the analysed system is to provide a certain volume of mineral water to the final user by means of 0.5-liter aseptic carton containers. The Functional Unit (FU) is assumed as *the delivery of 100 litres of mineral water (corresponding to 200 bottles)*. This FU will be used also for the comparison with the PET distribution system (Chapter 6).

4.3.3 System Boundary

The system boundary (Figure 8) includes:

- the manufacturing of the primary and secondary packages and the relative transportation to the bottling plant;
- the operations at the bottling plant (filling, capping, and packing into boxes);
- the distribution of aseptic carton water bottles (transportation from the bottling plant to the local distributor and then to the final user);

- the end of life of the primary and secondary packages, i.e. collection and waste treatment in dedicated facilities. In this stage, cases of multi-functionality related to the avoided productions due to the recovery of energy (incineration in a Waste-to-Energy plant) and materials (process of paper recycling) were solved by expanding the system boundary according to Finnveden et al. (2009).

Due to the lack of data, the life cycle of tertiary packaging for the transportation was not included. Moreover, also the extraction of 100 litres of mineral water was excluded since the focus of the study is the analysis of different packaging distribution systems all providing the same amount and type of water.

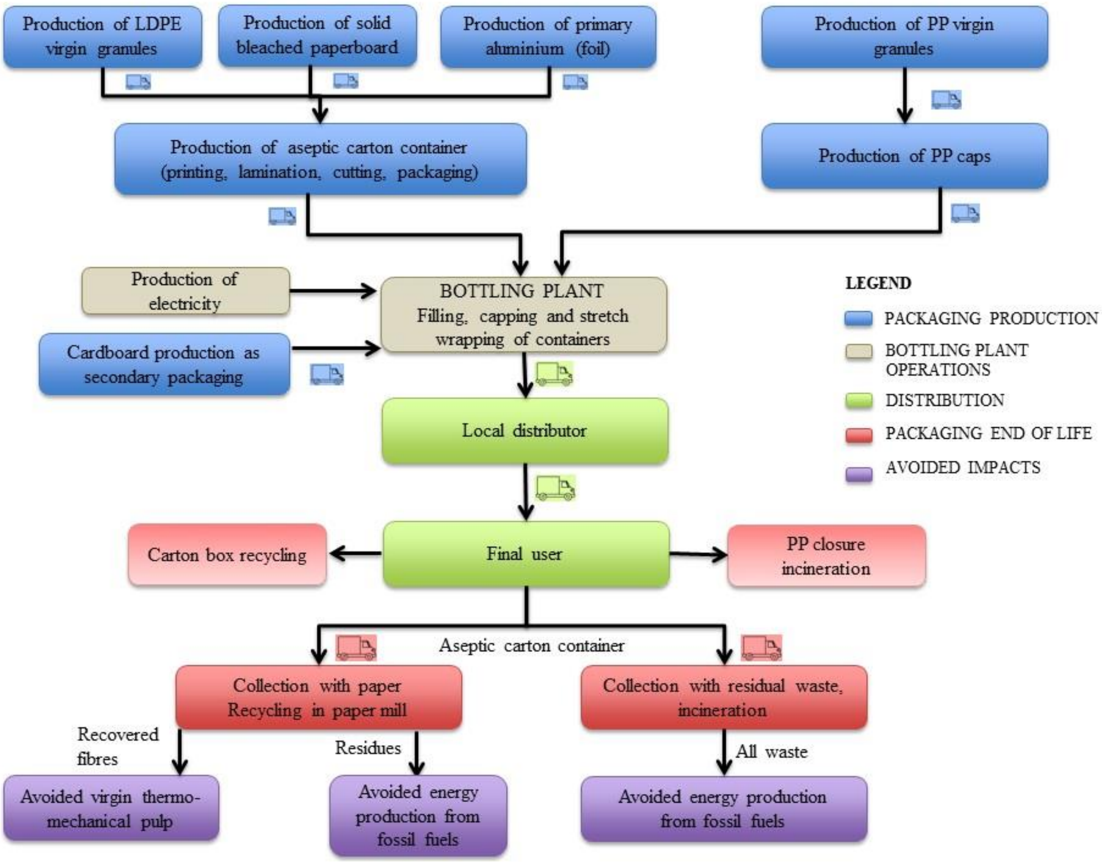


Figure 8. Analysed system with the relative boundary.

4.3.4 Data Quality

The geographical scope of the study is Northern Italy and collected data are related to the years 2017-2019. The foreground system was mainly described with data collected for other analysis and adopted here due to lack of data relative to aseptic carton. For the bottling plant operations literature data were available (Amienyo et al., 2013).

In particular, primary data about the primary and secondary packages (mass and material) were gathered by collecting samples of 0.5 L Tetra Pak Prisms and cartonboard boxes from Acqua Smeraldina. Regarding the distribution stage, the gross transported mass was derived from primary data of palletising reported by Acqua Smeraldina, while the average travelled distance was assumed the same as for the traditional PET distribution system, with which a comparison is made. In detail, Ferrarelle SpA, one of the first five bottled water companies in Italy, provided primary data on this stage reported in Grisales (2020). Finally, for the end of life of the packaging, inventory data from the waste treatment system in the northern Italy collected in previous works of the AWARE group (Grosso et al., 2012, Rigamonti et al., 2010) and from Italian waste management reports (Utilitalia-ISPRA, 2019) were mainly used. For the processes of the background system (such as electricity production), data from the ecoinvent 3.5 database (ecoinvent, 2018), *allocation cut-off by classification* approach were derived.

4.3.5 Selected Indicators

For the assessment, 14 impact categories from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018) were selected: climate change (CC), ozone depletion (OD), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer effects (HT_{NC}), human toxicity, cancer effects (HT_{C}), acidification (A), aquatic freshwater eutrophication (FE), aquatic marine eutrophication (ME), terrestrial eutrophication (TE), freshwater ecotoxicity (FEC), water scarcity (WS), resource use-energy carriers (RU_{EC}), resource use-mineral and metals (RU_{MM}).

- Climate change (CC) is defined in this context as the impact of human emissions on the "radiative forcing" (absorption of radiant heat) of the atmosphere. This leads to global warming and climate change. This category represents the ability of a greenhouse gas to influence changes in the global average air temperature at ground level and subsequent changes in various climate parameters and their effects (expressed in CO_2-equivalent units and over a specific time period: 100 years). The indicator is expressed in kg CO_2 equivalent, and collects the product of GWP (Global Warming Potential) of the substance for its mass;

- Ozone depletion (OD) refers to the depletion of the stratospheric ozone layer as a result of anthropogenic emissions. This allows a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful effects on health of humans, animals and ecosystems. This degradation of stratospheric ozone is due to emissions of ozone-depleting substances, such as chlorine and bromine containing gases of long life (e.g. CFC, HCFC, halon). It is calculated through the product between the mass of the substance by its ODP coefficient (Ozone Depletion Potential). This indicator is expressed in kg CFC-11 equivalent;
- Photochemical ozone formation (POF) refers to the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOC) and carbon monoxide (CO) in presence of nitrogen oxides (NO_x) and light sunny. High ground-level tropospheric ozone concentrations are detrimental to vegetation, human respiratory tract and artificial materials through the reaction with organic materials. Its unit of measurement is defined as kg NMVOC;
- Particulate matter (PM) where all volatile substances in the atmosphere are taken into account that fall into the category of particulate matter (PM) and also adverse effects on human health caused by emissions from both particulate matter and its precursors (NO_x, SO_x, NH_3). Its unit of measurement is defined as kg $PM_{2.5}$ equivalent;
- Non-cancer human health effects (HT_{NC}). This category takes into account the adverse effects on human health caused by the intake of toxic substances by inhalation of air, ingestion of food/water, skin penetration, insofar as they are non-carcinogenic substances, not caused by particulate matter/smog caused by emissions of inorganic substances or ionizing radiation. Its unit of measure is defined as CTUh (Comparative Toxic Unit for Humans);
- Cancer human health effects (HT_C). This category takes into account the adverse effects on human health caused by the intake of toxic substances by inhalation of air,

ingestion of food/water, skin penetration, insofar as they are carcinogenic substances. Its unit of measure is defined as CTUh;

- Terrestrial and freshwater Acidification (A). This indicator is used to monitor the level of impact of acidifying substances on the environment. Emissions of NOx, NH_3 and SOx result in the release of hydrogen ions when the gases are mineralized. Protons promote the acidification of soils and water, if released in areas where the buffer capacity is low, resulting in forest deterioration and acidification of lakes. The unit of measurement used is mol H^+ eq;
- Freshwater Eutrophication (FE). This category takes into account substances that contribute to freshwater eutrophication and especially those that have a certain concentration of nitrogen and phosphorus. Its unit of measure is defined as kg P eq;
- Marine eutrophication (ME). This category takes into account nutrients (mainly nitrogen and phosphorus) from sewage and fertilized agricultural soils accelerating the growth of algae and other vegetation in marine environments. Its unit of measure is defined as kg N eq;
- Terrestrial Eutrophication (TE). This indicator takes into account substances that contribute to terrestrial eutrophication and above all those having a certain nitrogen concentration. Its unit of measure is defined as mol N eq;
- Ecotoxicity freshwater (FEC). It considers the impacts from substances that are toxic to terrestrial and sedimentary aquatic ecosystems. Its unit of measure is defined as CTUe;
- Water scarcity (WS). This indicator considers the consumption of water and the consequent depletion of the resource. Its unit of measurement is defined as m^3 deprived.
- Resource use, energy carriers (RU_{EC}). It takes into account energy consumption from fuels. Its unit of measurement is defined as MJ;
- Resource use, mineral and metals (RU_{MM}). It takes into account the consumption of minerals and metals and the consequent depletion of resources. Its unit of measurement is defined as kg Sb eq.

4.3.6 Supporting Software for the Modelling

The analysis was carried out by means of the software SimaPro (version 9.0), designed by the Dutch company Pré Consultants (Amersfoort, The Netherlands); it was first implemented in 1990 and currently it is one of the main software for performing LCAs used by industries, universities and consulting societies in more than 60 countries in the world. It offers great flexibility thanks to different modelling parameters, that allow to perform an interactive analysis of the results (Grisales, 2020).

This software includes: (1) a user interface for modelling the product system; (2) different life cycle unit process databases; (3) an impact assessment database with data supporting several life cycle impact assessment methodologies; (4) a calculator that combines numbers from the databases in accordance with the modelling of the product system in the user interface (Herrmann & Moltesen, 2015).

4.4 Inventory Analysis

In the present chapter, the inventory associated to the different processes within the boundary of the system will be shown. In detail, the included stages are:

- life cycle of the aseptic carton container;
- life cycle of the closure of the bottle;
- life cycle of the corrugated cardboard box;
- bottling plant operations;
- distribution of the mineral water from the bottling plant to the final user.

4.4.7 Aseptic Carton Container Life Cycle

The average weight of the reference Aseptic carton container, format 0.5 litres, is equal to 21.5 grams/bottle (4.3 kg/FU), calculated by weighing some samples of the Tetra Pak Prism from Smeraldina brand.

Production stage

According to Tetra Pak indications, aseptic beverage carton consists of three main materials: 75% paper board, 20% Low-Density Polyethylene (LDPE), and 5% aluminium foil. In a dedicated converting plant, the paper board is printed and then the three materials are layered together through extrusion lamination. At the end of the process, the packaging is cut and then packed inside corrugated board boxes palletised with stretch film (Figure 9).

Once produced, aseptic carton is transported to the reference water bottling plant. The transport was modelled according to the Product Environmental Footprint (PEF) guidelines, in relation to the transport of empty containers from the supplier to the bottling plant (in this way a comparison with the PET bottles distribution system is possible): 350 km by lorry (size > 32 metric tons, Euro 4) and 39 km by freight train (European Commission, 2019).

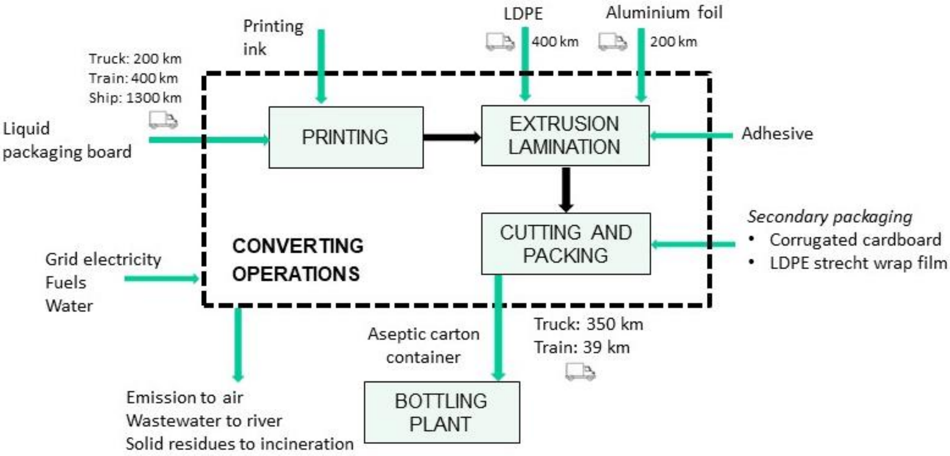


Figure 9. System boundary and main input and output flows associated to the production of the aseptic carton container ready for the filling.

The starting point for the inventory was the ecoinvent 3.5 dataset "*Liquid packaging board container {RER}| production*". Since this dataset is based on old literature sources (related to the year 2000 or earlier; Hischier, 2007), where possible, inventory data were updated according to the following more recent sources:

- Life Cycle Inventory (LCI) dataset of the Alliance for Beverage Cartons and the Environment (ACE, 2009). ACE prepared a European gate-to-gate LCI dataset for the production of beverage carton packaging. Data derive from 13 out of 19 European plants and the time coverage is the year 2005. The original LCI dataset is expressed per 1,000

m^2 of beverage carton ready for the transport to the fillers. Corresponding values in mass of packaging were obtained by considering a grammage equal to 200 g/m^2 typical for an Aseptic carton laminate (Grumezescu and Butu, 2019);

- inventory data from Cleary (2013). The author modelled the beverage carton manufacture according to the inventory data of the year 2002 published by Tetra Pak for its manufacturing facility in Dijon (France; Tetra Pak, 2003). The original LCI dataset is expressed per one unit of beverage carton ready for the transport to the fillers. Corresponding values were calculated by considering in our case a weight of the packaging equal to 21.5 grams.
- energy consumption data from Xie et al. (2011). The study calculated the environmental impacts associated to the life cycle assessment of the milk packaging system, based on paper-polyethylene-aluminium laminated containers. The geographical context was China.

Table 4 summaries the inventory of the beverage carton production (main flows and related amount, hypotheses and modelling in the SimaPro software).

Table 4.Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro in relation to the production of 1 gram of aseptic carton packaging ready for the filling.

Raw materials request		**Amount per 1 gram of aseptic carton packaging**	**Unit of measure**	**Explanations and assumptions**
Production of liquid packaging paper board *Solid bleached board {RER}| production*		0.796	g	75% of the packaging is paper. The value includes also the amount of residues from the process (0.0615 g, of which 75% is assumed to be paper)
Transportation of the paper board to the converter	Truck: *Transport, freight, lorry, unspecified {RER}| market for*	0.796 × 200	g × km	Distances and ways of transport reported in ACE (2009)
	Train: *Transport, freight train {RER}| market group*	0.796 × 400	g × km	
	Ship: *Transport, freight, sea, transoceanic ship {GLO}| processing*	0.796 × 1300	g × km	

Request of LDPE *Polyethylene, low density, granulate {RER}| production*	0.212	g	20% of the packaging is composed of LDPE on the average. The value includes also the amount of residues
Transportation of the LDPE to the converter by truck *Transport, freight, lorry, unspecified {RER}| market for*	0.212 × 400	g × km	Distances and ways of transport reported in ACE (2009)
Request of aluminium *Aluminium, alloy {GLO}| aluminium ingot, primary, to market*	0.053	g	5% of the packaging is aluminium. The value includes also the amount of residues from the process. The partition between cast (32%) and wrought alloy (68%) derives from the ecoinvent 3.5 dataset
Transportation of the aluminium to the converter by truck *Transport, freight, lorry, unspecified {RER}| market for*	0.053 × 250	g × km	Distances and ways of transport reported in ACE (2009)
Auxiliary request	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Request of water *Water, unspecified natural origin, IT*	0.41	ml	Average value obtained from ACE (2009) and Cleary (2013)
Request of electricity from the Italian grid *Electricity, medium voltage {IT}| market for*	0.37	Wh	Value obtained from the average of ACE (2009), Cleary (2013) and Xie et al. (2011)
Natural gas request and combustion *Heat, district or industrial, natural gas {RER}| market group for*	573	J	Value from ACE (2009)
LPG and fuel oil request and combustion *Heat, district or industrial, other than natural gas {RER}| market group for*	114	J	Value from ACE (2009)
Converting plant life cycle *Packaging box factory {RER}| construction*	$1.43*10^{-12}$	units	Value from the ecoinvent 3.5 dataset in absence of other inventory data
Printing ink request *Printing ink, offset, without solvent, in 47.5% solution state {RER}| market for*	6.11	mg	Average value obtained from ACE (2009) and Cleary (2013)
Adhesive request *Solvent, organic {GLO}| market for*	2.2	mg	Value from the original ecoinvent dataset in absence of more recent data
Secondary packaging request	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Request of corrugated cardboard boxes *Corrugated board box {RER}| market for*	50	mg	Value derived from ACE (2009)
Request of stretch wrap film *Packaging film, low density polyethylene {RER}| production*	3	mg	Value derived from ACE (2009)
Transport of the ready packaging to the reference bottling plant	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Lorry transport *Transport, freight, lorry, unspecified {RER}| market for*	1 × 350	g × km	The mode of transport was modelled according to the PEF guidelines, in relation to the transport of empty bottles from the supplier to the bottling plant
Train transport *Transport, freight train {RER}| market group for transport*	1 × 39	g × km	
Emission to air of the converting plant[1]	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Halon 1301	$4.85*10^{-7}$	g	

Chlorofluorocarbon-11 (CFC-11)	$4.85*10^{-7}$	g	Value from the ecoinvent 3.5 dataset in absence of more recent data
Non-methane volatile organic (NMVOC) compounds	0.30	mg	Value from ACE (2009)
Water vapour	$6.1*10^{-2}$	ml	15% of the consumed water according to the 3.5 ecoinvent dataset
Wastewater of the converting plant	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Unpolluted wastewater (modelled as emission into a river)	0.349	ml	85% of the consumed water according to the 3.5 ecoinvent dataset
Solid residues of the converting plant	**Amount per 1 gram**	**Unit of measure**	**Explanations and assumptions**
Residues to incineration *Municipal solid waste {IT} treatment of incineration*	0.0615	g	% of residues obtained from ACE (2009) and Cleary (2013)

[1] Emissions related to the printing process (NMVOC) and from CFC/HCFC leakages (CFC-11 equivalent emissions). CFC-11 equivalent emissions are expressed here as 50% CFC-11 and 50% Halon 1301 (Hischier, 2007). Fuel combustion emissions are already included in the relative ecoinvent heating dataset.

End of life stage

As regards the end of life, the following three different scenarios of aseptic carton waste management were modelled according to the available inventory data:

- SCENARIO 1 - collection and treatment with the residual waste;
- SCENARIO 2 - collection together with paper and treatment in a conventional paper mill;
- SCENARIO 3 - collection together with paper and treatment in a paper mill dedicated to the recovery of Aseptic carton.

In SCENARIO 1 (Figure 10), the container is collected with the Residual Waste (RW) and sent to an incineration plant with energy recovery (the most common RW treatment in northern Italy). This scenario is considered of particular interest, since according to a recent research performed by Comieco (2019), about 21% of the Italian citizens still disposes the Aseptic carton waste in the residual garbage bin.

In the modelling (Table 5), a door-to-door collection of the waste was considered, with the transport distance and the type of trucks typically used in northern Italy (context of Regione Lombardia, Grosso et al., 2012). The waste is conveyed to a municipal deposit and then transported to the Waste-to-Energy plant with big trucks (> 32 metric tons). For this transportation step, an average travelled distance of 100 km was assumed, taking into account the number and the spatial distribution of incinerators in northern Italy. The final treatment in the WTE plant was then modelled according to an ecoinvent dataset specifically built for the aseptic carton container. This dataset includes the burdens of paper, aluminium, and plastic incineration (consumption of water, chemicals, auxiliary fuel, emissions to air and disposal of the bottom ash, fly ash and air pollution control residues) and the recovery of energy.

The amount of recovered energy was calculated considering a lower heating value for the laminated beverage container equal to 21 MJ/kg (Campbell-Platt, 2017) and the average net conversion efficiency of WTE plants in northern Italy (η_{EL}=19.3% and η_{TH}=14.2%; UTILITALIA-ISPRA, 2019). The avoided electricity was modelled as the one produced through a natural gas combined cycle power plant, the marginal technology in Italy (Terna, 2018).

The produced heat was assumed to be delivered to the district heating network in the area of the incinerator, characterized by an overall 10% loss for the distribution and the heat exchange at the households. The avoided technology is a domestic natural gas-fired boiler, with emission factors mainly specific for the Italian context (details in the Annex 1).

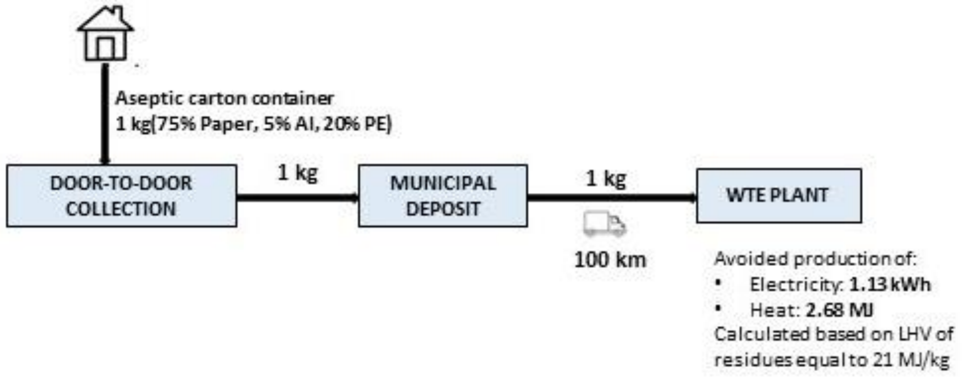


Figure 10. Main stages of the scenario 1 of aseptic carton end of life and relative mass balance.

Table 5. Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro for the scenario 1 of aseptic carton end of life (collection with RW and incineration).

Transportation stages		**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Door-to-door collection of residual waste	Big truck: *Transport, freight, lorry 16-32 metric ton* [1]	$0.409/2*15.4*10^{-3}$	kg*km	According to primary data collected for Lombardy Region, 15.4 km per ton of RW are travelled during the collection. 40.9% of the trip is performed by big trucks and 59.1% by small vehicles. It was assumed that the truck is empty for half of the trip and full for the rest of the trip
	Small truck: *Transport, freight, light commercial vehicle (Europe without Switzerland)| market for*	$0.591/2*15.4*10^{-3}$		
Transportation from the municipal deposit to the WTE plant: *Transport, freight, lorry >32 metric ton* [2]		1*100	kg*km	It was assumed a distance of 100 km considering the widespread presence of WTE plants in the northern Italy
Treatment in a WTE plant		**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Burdens of paper incineration *Waste paperboard {CH}| treatment of, municipal incineration*		0.75	kg	Calculation based on the average composition of the waste: 75% paper, 20% LDPE, and 5% aluminium
Burdens of aluminium incineration *Residue aluminium {Europe without Switzerland}| treatment of residue aluminium, municipal incineration*		0.05	kg	
Burdens of polyethylene incineration *waste polyethylene {CH}| treatment of, municipal incineration*		0.2	kg	
Recovery of electricity: *Electricity, high voltage (IT)|electricity production, natural gas, combined cycle power plant*		1.13	kWh	- LHV of Aseptic carton: 21 MJ/kg - Net electrical efficiency of WTE plants in the northern Italy: 19.3%
Recovery of heat: the dataset was specially built (see Annex 1)		2.68	MJ	- LHV of Aseptic carton: 21 MJ/kg - Net thermal efficiency of WTE plants in the northern Italy: 14.2% - 10% losses for the distribution

[1] Euro mix of trucks *16-32 metric tons* in the northern Italy: Euro 3 and previous classes - 65%; Euro 4 - 8%; Euro 5 - 18%; Euro 6 - 9%. [2] Euro mix of trucks > *32 metric tons* in the northern Italy: Euro 3 and previous classes - 79%; Euro 4 - 10%; Euro 5 - 7%; Euro 6 - 3% (ACI, 2019).

In SCENARIO 2 (Figure 11), the container is supposed to be collected with paper separated at the source, sent to a paper sorting plant (for the removal of impurities and pressing of the waste) and then to a conventional paper mill for the recycling. About 27 paper mills in Italy can receive aseptic carton containers mixed with other types of paper waste. The maximum accepted quantity of aseptic carton is about 3-4% of the total paper processed and about only 30-40% of the fibres are recovered (Casti et al., 2014). The residues (aluminium and plastic films, together with the fibres not recovered) are destined to WTE plants since the recovery in the cement industry is not yet applied in Italy (Personal communication with Lorenzo Nannariello, Sustainability Manager of Tetra Pak Italia).

In the modelling, a door-to-door collection of the paper was implemented according to the collection distance and the type of trucks typically used in northern Italy (Grosso et al., 2012). The transportation of the waste to the sorting plant, the conventional paper mill and the WTE plant was assumed to be performed by big trucks (>32 metric tonnes). The distance between the municipal deposit and the paper sorting plant was assumed equal to 20 km, according to recent indications of Comieco (2018), while for the other transportation stages a distance of 100 km was assumed.

Burdens of the sorting process (consumption of lubricating oil, diesel, and electricity) were calculated according to primary data provided by some Italian facilities in a previous work of the AWARE group (Verì, 2019). Moreover, a 100% sorting efficiency was assumed considering that the analysed container is completely made of aseptic carton.

As regards the recycling process, water, fuel and electricity consumptions were modelled according to the BREF document related to the production of pulp, paper, and board (Suhr et al., 2015) and to data reported in Rigamonti and Grosso (2009). The fibres recovered by the process (35% of the input paper; Casti et al., 2014) were assumed to avoid the production of virgin thermomechanical pulp with a substitution ratio equal to 1:0.83 by mass, based on the maximum number of recycling cycles which a single paper fibre can undergo, equal to five (Rigamonti et al., 2010).

The amount of residues was calculated based on a process mass balance (65% of input paper, 100% of input Al and PE), considering that the dry content amounts to 50% of the gross weight due to the absorption of water in the pulper stage (Casti et al., 2014). Its treatment in a WTE plant was thus modelled considering a lower heating value equal to 10.85 MJ/kg

(Table 7) and the average net conversion efficiencies of WTE plants in northern Italy. Details of Scenario 2 modelling data are reported in Table 6.

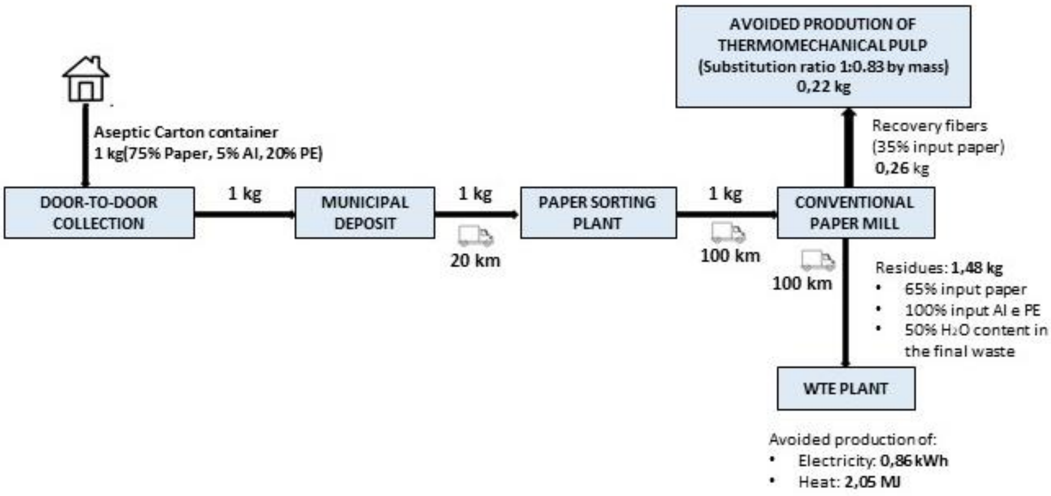


Figure 11. Main stages of the scenario 2 of Aseptic carton end of life and relative mass balance.

Table 6. Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro software for the Scenario 2 of aseptic carton end of life.

Transportation stages		**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Door-to-door collection of paper	Big truck: *Transport, freight, lorry 16-32 metric ton*[1]	$0.411/2*27*10^{-3}$	kg*km	According to primary data collected for Lombardy Region, 27 km per ton of paper are travelled during the collection. 41.1% of the trip is performed by big trucks; 58.9% by small vehicles. It was assumed that the truck is empty for half of the trip and full for the rest of the trip
	Small truck: *Transport, freight, light commercial vehicle (Europe without Switzerland)| market for*	$0.589/2*27*10^{-3}$		
Transportation to the different waste facilities: *Transport, freight, lorry >32 metric ton*[1]		Municipal deposit-sorting: 1*20	kg*km	The distance from the municipal deposit to the sorting plant derives from Comieco indications. For the other waste facilities, it was assumed a distance of 100 km
		Sorting-Recycling: 1*100		
		Recycling-WTE plant: 1.5*100		

Sorting process	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Consumption of lubricating oil *Lubricating oil {RER}| production*	49	mg	Primary data from some sorting facilities in Italy (Verì, 2019)
Consumption of electricity *Electricity, medium voltage {IT}| market for*	58	Wh	
Consumption of diesel and burning *Diesel, burned in building machine {GLO}| processing*	428	kJ	

Recycling process	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Consumption of electricity *Electricity, medium voltage {IT}| market for*	200	Wh	BREF document related to the production of pulp, paper, and board (Suhr et al., 2015)
Request of water *Tap water {Europe without Switzerland}| tap water production, underground water without treatment*	4.2	kg	
Consumption of diesel and burning *Diesel, burned in building machine {GLO}| processing*	17.9	kJ	Rigamonti and Grosso (2009)
Output flow of residues sent to incineration[2]	Paper: 0.65*750 g Al: 50 g PE: 200 g Water: 737.5 g Total: 1475 g	g	- 65% of the input paper is not recovered; - 100% of the input Al and PE become residues; - the dry content of the waste is 50% due to the water absorption
Fibres recovered and used in substitution of virgin pulp *Thermo-mechanical pulp {RER}| production* (modelled as avoided product)	218	g	- 1 kg of Aseptic carton contains 750 grams of paper; - Recovered paper: 35% by mass - Substitution ratio by mass 1:0.83
Wastewater *Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year*	3	kg	BREF document related to the production of pulp, paper, and board (Suhr et al., 2015)

[1] Euro mix of trucks in northern Italy. [2] The treatment in the WTE plant was modelled according to an ecoinvent dataset specifically built, including the burdens of paper, aluminium, and plastic incineration and the energy recovery from the waste (LHV equal to 10.85 MJ/kg residue; see Table 7).

Table 7. Calculation of the LHV for the flow of residues produced by the conventional paper mill and sent to incineration.

Component of the residue sent to incineration	**Amount (g/kg input Aseptic carton)**	**% in the residue**	**Lower heating value (MJ/kg)**
Paper	487.5	33.0%	15.92 - ecoinvent 3.5 dataset
Aluminium foil	50	3.4%	The aluminium in thin sheets behaves similarly to the Al powder (31 MJ/kg; Grosso, 2019)
Plastic - Polyethylene	200	13.6%	42.47 - ecoinvent 3.5 dataset
Water	737.5	50%	- 2.5
Total	1475	100%	10.85

In SCENARIO 3 (Figure 12), the container is supposed to be collected together with paper separated at source, sent to a paper sorting plant (removal of impurities and pressing of the waste) and then to a paper mill dedicated to the aseptic carton recycling. In Italy, there are only two facilities of this type (Cartiera Saci and Cartiera Lucart Group) but none of them provided primary data on the process. Therefore, the scenario was modelled according to literature data and theoretical assumptions.

In the modelling, the inventory data and assumptions for the waste paper collection, the transportation to the sorting plant and the paper sorting process were assumed the same as those of scenario 2.

The transportation distance between the sorting plant and the recycling facility was arbitrarily increased from 100 km to 200 km, to take into account the presence of only two dedicated facilities in northern Italy.

As regards the recycling process (Table 8), the energy and water consumptions were maintained the same as those of the conventional paper mill (Table 6) in absence of specific data. Subsequently a sensitivity analysis was carried out on the water and energy consumption of a dedicated paper mill, starting from those of a conventional one. The amount of cellulose material recovered from the post-consumer aseptic packaging was assumed equal to 90% of the total fibres content (675 g/kg aseptic carton waste; Xie et al., 2013). The fibres recovered by the process were assumed to avoid the production of virgin thermomechanical pulp with a substitution ratio by mass equal to 1:0.83 (Rigamonti et al., 2010).

The amount of residues was calculated based on a process mass balance (10% of input paper, 100% of input Al and PE), considering that the dry content amounts to 50% of the gross weight due to the absorption of water in the pulper stage (Casti et al., 2014). Its treatment in a WTE plant was thus modelled considering a lower heating value equal to 15.90 MJ/kg (Table 9) and the average net conversion efficiencies of WTE plants in northern Italy.

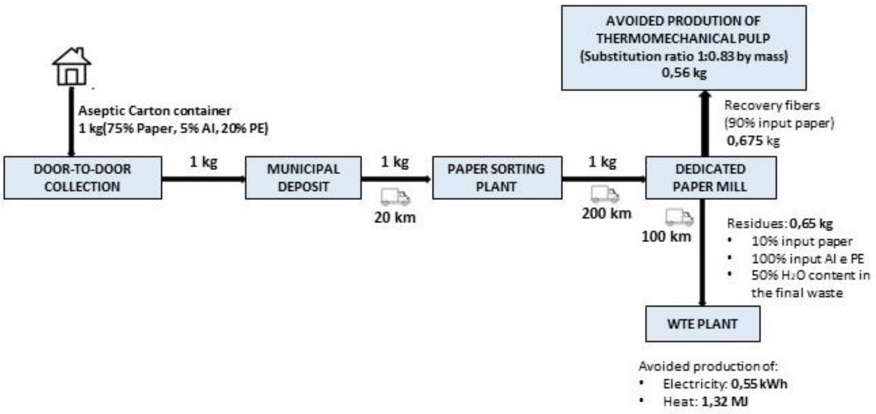


Figure 12. Main stages of the scenario 3 of Aseptic carton end of life and relative mass balance.

Table 8. Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro software for the Scenario 3 of aseptic carton end of life.

Recycling process	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Consumption of electricity *Electricity, medium voltage {IT}| market for*	200	Wh	BREF document related to the production of pulp, paper, and board (Suhr et al., 2015)
Request of water *Tap water {Europe without Switzerland}| tap water production, underground water without treatment*	4.2	kg	
Consumption of diesel and burning *Diesel, burned in building machine {GLO}| processing*	17.9	kJ	Rigamonti and Grosso (2009)

Output flow of residues sent to incineration	Paper: 0.10*750 g Al: 50 g PE: 200 g Water: 325 g Total: 650 g	g	- 10% of the input paper is not recovered; - 100% of the input Al and PE become residues; - the dry content of the waste is 50% due to the water absorption
Fibres recovered and used in substitution of virgin pulp *Thermo-mechanical pulp {RER}| production* (modelled as avoided product)	560	g	- 1 kg of Aseptic carton contains 750 grams of paper; - Recovered paper: 90% by mass - Substitution ratio by mass 1:0.83
Wastewater *Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year*	3	kg	BREF document related to the production of pulp, paper, and board (Suhr et al., 2015)

Table 9. Calculation of the LHV for the flow of residues produced by the dedicated paper mill and sent to incineration.

Component of the residue sent to incineration	**Amount (g/kg input Aseptic carton)**	**% in the residue**	**Lower heating value (MJ/kg)**
Paper	75	11.5%	15.92 - ecoinvent 3.5 dataset
Aluminium foil	50	7.7%	The aluminium in thin sheets behaves similarly to the powder (31 MJ/kg; Grosso, 2019)
Plastic - Polyethylene	200	30.8%	42.47 - ecoinvent 3.5 dataset
Water	325	50%	- 2.5
Total	650	100%	15.90

4.4.8 Life Cycle of the Closure

The manufacturing process of the closure (Table 10) begins with the production of virgin PP granules that are then subjected to an injection moulding process, with an efficiency of 99.4% (ecoinvent, 2018). As a result, caps with an average weight of 3.5 g/bottle (0.7 kg/FU) are obtained and then transported to the reference bottling plant. Caps transportation was modelled according to the ways indicated by the PEF guidelines for the transportation of packages from the manufacturing plant to the filling plant (European Commission, 2019). Regarding the end of life (Table 11), it was assumed that all caps are incinerated in a WTE plant after being sorted as plasmix from plastic waste separately collected. Despite the general indication of separating the closures from the container and disposing them together with plastics, some citizens will dispose them in the residual waste or in the paper together with the aseptic carton container; in both cases the closures will be sent to incineration directly (RW flow) or after a sorting process (paper collection). However, these last two ways of collection were not modelled due the generally low contribution to the impacts given by the life cycle of the closure. Details of the inventory and modelling are reported in Tables 10 and 11.

Table 10. Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro for the production of the PP closure.

Closure production process	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
PP virgin granulate production *Polypropylene, granulate {RER}| production*	1/0.994=1.01	kg	0.994 is the efficiency of the injection moulding operation (ecoinvent, 2018)
Production of the closure from granulate by injection moulding *Injection moulding {RER}| processing*	1/0.994=1.01	kg	Passage from granules to closure
Transportation of the closure to the bottling plant by lorry *Transport, freight, lorry > 32 metric ton, euro4 (RER) market for transport*	230*1	kg × km	Transport indications given by the PEF Guidelines (European Commission, 2019)
Transportation of the closure to the bottling plant by train *Transport, freight train (RER) market group for transport,*	280*1	kg × km	

Table 11. Inventory data, adopted assumptions and list of the ecoinvent datasets (version 3.5) implemented at SimaPro for the end of life of the PP closure.

Transportation stages		**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Door-to-door collection of plastic waste	Big truck: *Transport, freight, lorry 16-32 metric ton*	$0.406/2*48.8*10^{-3}$	kg*km	According to primary data collected for Lombardy Region, 48.8 km per ton of plastic are travelled during the collection. 40.6% of the trip is performed by

Small truck: *Transport, freight, light commercial vehicle (Europe without Switzerland)| market for*	$0.594/2*48.8*10^{-3}$		big trucks and 59.4% by small vehicles. It was assumed that the truck is empty for half of the trip and full for the rest of the trip
Transportation from the municipal deposit to the plastic sorting plant and then to incineration: *Transport, freight, lorry >32 metric ton*	1*100	kg*km	It was assumed 100 km considering the widespread presence of waste incineration facilities in northern Italy
Sorting operations for plastic	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Consumption of electricity *Electricity, medium voltage {IT}| market for*	29	Wh	Primary data from facilities in the northern Italy (Rigamonti and Grosso, 2009)
Consumption of diesel and its combustion *Diesel, burned in building machine {GLO}| processing*	84	kJ	
Treatment in a WTE plant	**Amount per 1 kg**	**Unit of measure**	**Explanations and assumptions**
Burdens of PP incineration *Waste polypropylene {CH}| treatment of, municipal incineration*	1	kg	
Recovery of electricity: *Electricity, high voltage (IT)|electricity production, natural gas, combined cycle power plant*	1.76	kWh	- LHV: 32.78 MJ/kg (ecoinvent) - Net electrical efficiency of WTE plants in the northern Italy: 19.3%
Recovery of heat: the dataset was specially built (see Annex 1)	4.19	MJ	- LHV: 32.78 MJ/kg (ecoinvent) - Net thermal efficiency of WTE plants in the northern Italy: 14.2% - 10% losses for the distribution

4.4.9 Life Cycle of the Corrugated Cardboard Box

For transportation purposes, filled aseptic carton containers are placed inside disposable corrugated cardboard boxes (secondary packaging). Each box normally includes 24 containers and has an average weight of 350 g/box (2.9 kg/FU). The production of the box was modelled in the SimaPro software with the ecoinvent 3.5 dataset *Corrugated board box {RER}| production*, considering the semi-chemical paper as a fluting medium and kraftliner board (virgin raw material). Regarding the end of life, it was assumed that the box is recycled in a conventional paper mill according to the inventory data of water, electricity and diesel consumption reported in Table 6. In this case, fibres are recovered with a recycling efficiency of 89% (Rigamonti et al., 2010) and will avoid the production of thermomechanical virgin pulp with a substitution ratio equal to 1:0.83 in mass.

4.4.10 Bottling Plant Operations

Acqua Smeraldina has not provided inventory data about the electricity consumption of the bottling facility (for filling, capping, and packing the aseptic carton containers) and are not available from previous literature studies. For this reason, the amount of electricity required for filling and packing glass bottles and aluminium cans (24 Wh/L equal to 12 Wh/aseptic carton container, Amienyo et al., 2013) was used as a first approximation. The value proposed for PET bottles was not considered since it includes the energy consumption for blowing the preforms (this stage is not required in case of aseptic carton containers). When modelling this consumption, the manufacturing plant was considered to be connected to the Italian grid (ecoinvent dataset *Electricity, medium voltage {IT}| market for*).

4.4.11 Distribution from The Bottling Plant to The Local Distributor

For this stage, inventory data were collected about the following aspects:

- gross transported mass. An average gross transported mass equal to 0.559 kg/container (111.8 kg/FU) was calculated according to the pallet composition (gross weight and number of bottles) reported by Acqua Smeraldina in its web site;
- average travelled distance. We have assumed 300 km, the value used for the distribution of PET bottles in the northern Italian market (complete data are reported in Annex 2). This choice was made supposing that all companies of bottled water operating in the northern Italian market substitute PET bottles with Aseptic carton containers;
- type of trucks used. This information was directly derived from a personal communication with Ferrarelle SpA (Grisales, 2020). This company uses trucks with a capacity higher than 32 metric tons and the Euro mix reported in Figure 13.

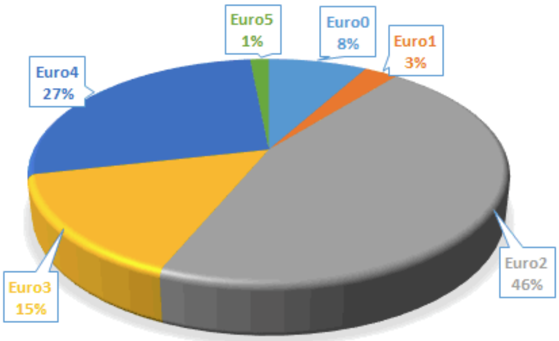


Figure 13. Euro mix assumed for trucks > 32 metric tons used in the transportation of the mineral water to the local distributors (Grisales, 2020).

4.4.12 Distribution from The Local Distributor to The Final User

According to ACI, 2019 for the Italian context, the delivering of PET water bottles from the local distributor to the final user (Horeca sector) generally occurs with small lorries along an average trip of 30 km (for hypothesis the truck is fully loaded for 15 km and empty for the remaining 15 km). This data was assumed also for aseptic carton. This step was modelled in the SimaPro with the ecoinvent dataset *Transport, freight, lorry 3.5-7.5 metric ton|{RER}* considering the current Euro mix of the Northern Italy (Euro 3 and previous classes: 73%, Euro 4: 12%, Euro 5: 11% and Euro 6: 4%, ACI, 2019).

Chapter 5

Analysis of the Results

In this chapter, the results of the LCA on the water distribution systems described in Chapter 4 are shown and discussed. The total potential impacts are first reported, then a contribution analysis is carried out in order to understand which processes influenced most the results (Chapter 5.1). Three scenarios for end-of-life of aseptic carton container are analysed by comparing its treatment with the residual waste and the collection and processing with paper separated at the source (recycled in a conventional paper mill or in a dedicated paper mill).

Then, a sensitivity analysis on energy and water consumption of the dedicated paper mill is performed (Chapter 5.2). Starting from the assumption of having the same consumption as that of the conventional paper mill, they were increased to find threshold values to define the best scenario.

5.1 Potential Impacts of the Aseptic Carton Distribution System

Table 12 reports the potential impacts related to the distribution system of water in 0.5 litres aseptic carton containers considering Scenario 1. The impacts refer to the distribution of 100 litres of mineral water (reference flow of 200 containers) and include the burdens of:

- the life cycle of the aseptic carton container, of the PP closure, and of the corrugated card box used for the transportation;
- the bottling plant operations (filling of the container, capping, and packing);

- the transportation from the bottling plant to the local distributor and then from the local distributor to the final user (Horeca sector).

In Scenario 1, all containers are collected with the Residual Waste (RW) and sent to an incineration plant with energy recovery. The impacts variation associated to the treatment of post-consumer aseptic carton in a conventional or dedicated paper mill is analysed below (Paragraph 5.1.1).

Table 12. Potential environmental impacts per stage (absolute and relative) for the distribution system of 0.5L Aseptic carton containers. Absolute values are expressed per FU (the distribution of 100 litres of water).

Impact indicator		**Life cycle of Aseptic carton container**		**Life cycle of PP closure**		**Bottling plant operations**		**Life cycle of corrugated cardboard box**		**Transportation from the bottling plant to the local distributor**		**Transportation from the local distributor to the final user**		**Total**
CC	kg CO_2 eq	10.90	55%	3.35	17%	1.09	6%	0.45	2%	3.05	15%	0.86	4%	19.70
OD	kg CFC11 eq	3.41E-05	97%	1.96E-08	0%	1.29E-07	0%	9.58E-08	0%	7.36E-07	2%	1.86E-07	1%	3.52E-05
POF	kg NMVOC eq	4.46E-02	51%	7.64E-03	9%	2.59E-03	3%	4.10E-03	5%	2.30E-02	26%	5.29E-03	6%	8.72E-02
PM	disease inc.	1.09E-06	52%	8.81E-08	4%	6.25E-08	3%	4.36E-07	21%	3.40E-07	16%	6.13E-08	3%	2.07E-06
HT_{NC}	CTUh	2.44E-06	68%	9.86E-08	3%	7.00E-08	2%	3.03E-07	8%	5.61E-07	16%	1.10E-07	3%	3.58E-06
HT_{C}	CTUh	3.31E-07	82%	2.17E-08	5%	5.36E-09	1%	1.32E-08	3%	2.08E-08	5%	9.43E-09	2%	4.02E-07
A	mol H^+ eq	7.31E-02	60%	1.00E-02	8%	1.18E-02	10%	1.83E-03	2%	1.97E-02	16%	4.98E-03	4%	1.21E-01
FE	kg P eq	3.43E-03	79%	5.71E-04	13%	3.23E-04	7%	0.00E+00	0%	2.40E-04	6%	9.51E-05	2%	4.66E-03
ME	kg N eq	1.39E-02	50%	1.76E-03	6%	1.04E-03	4%	2.11E-03	8%	7.39E-03	26%	1.73E-03	6%	2.79E-02
TE	mol N eq	0.17	50%	0.02	6%	0.04	11%	0.01	3%	0.08	24%	0.02	6%	0.34
FEC	CTUe	12.45	45%	1.49	5%	0.23	1%	1.80	7%	10.15	37%	1.40	5%	27.52
WS	m^3 depriv.	6.38	72%	0.82	9%	0.79	9%	0.41	5%	0.36	4%	0.09	1%	8.86
RU_{EC}	MJ	135.29	52%	54.82	21%	15.95	6%	0.00	0%	48.72	19%	12.81	5%	267.58
RU_{MM}	kg Sb eq	2.22E-05	57%	1.41E-06	4%	4.62E-07	1%	4.36E-06	11%	5.65E-06	15%	4.65E-06	12%	3.88E-05

The impact contribution analysis reveals that the life cycle of the aseptic carton container is the most important burden to the total impact of the system in all the impact categories. Depending on the category, this contribution ranges from 45% (freshwater ecotoxicity) to 97% (ozone depletion) (Table 12 and Figure 14).

Another important stage in terms of impacts is the transportation of the bottles from the bottling plant to the local distributor (300 km on average). Its contribution is higher than 15% in eight impact categories (photochemical ozone formation, particulate matter, non-cancer human toxicity, acidification, marine and terrestrial eutrophication, freshwater ecotoxicity, and resource use-minerals & metals) and reaches a maximum contribution of 37% in the freshwater ecotoxicity indicator.

The life cycle of the closure shows a non-negligible contribution in the impact categories of climate change (17%), freshwater eutrophication (13%) and resource use, energy carriers (21%). It should be noted also the burden of the corrugated cardboard box life cycle in the particulate matter category (21% of the total impact).

The contribution of the other stages (bottling plant operations and the transportation from the local distributor to the final user) is generally contained within 10% (Figure 14).

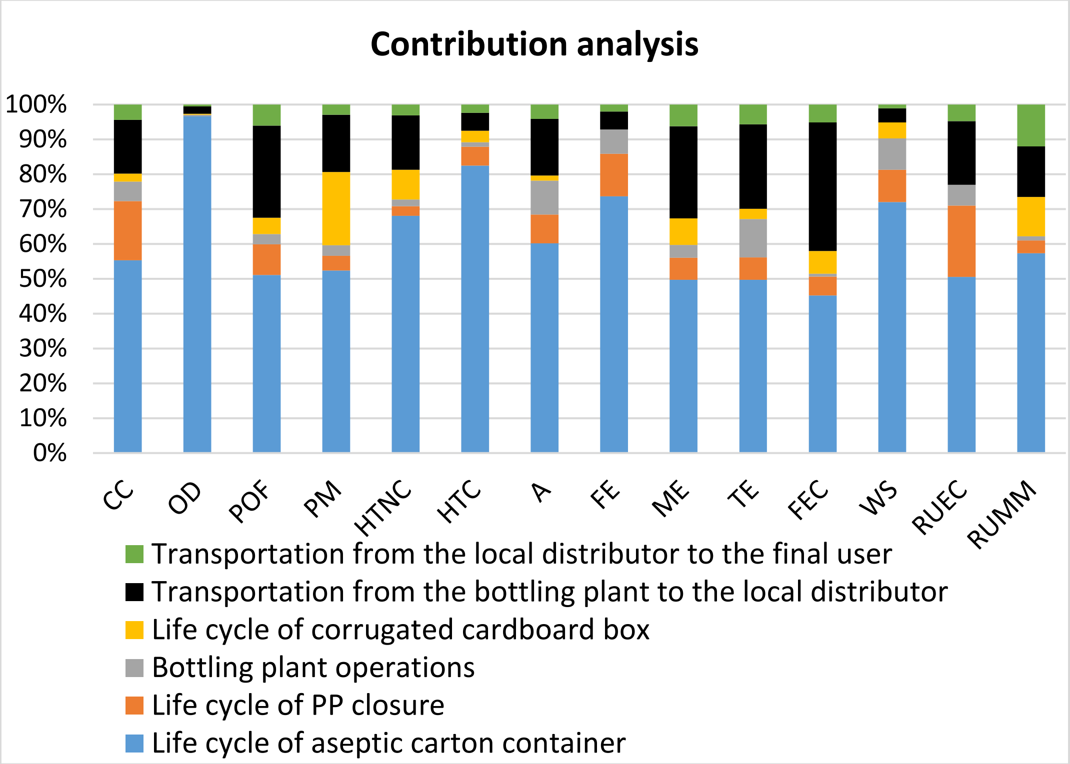


Figure 14. Percentage contribution of the different stages to the total impacts of the distribution system based on 0.5L Aseptic carton bottles (scenario related to the incineration of post-consumer containers).

Focusing only on the aseptic carton container life cycle, the main impacting stages result the production and transportation of the paper boards and aluminium foils used for the manufacturing of the aseptic carton. The stage of aluminium production and transportation shows a contribution higher than 25% in most of the indicators, reaching 50% in the indicator of resource use-mineral & metals and 63% in the cancer human toxicity category. Though the amount of aluminium needed for the manufacturing of aseptic carton is low (only 5% of the container), its production implies a significant burden since it is primary aluminium, considering the use in the food & beverage sector.

The contribution of the paper board is higher than 20% in each analysed impact category except for the ozone depletion indicator. In particular, a significant burden is visible in the water scarcity category (68% of the total impact), due to the high consumption of water: the production of 1 kg of solid bleached board requires 81 litres of water (ecoinvent dataset used in the modelling).

A separate discussion should be done for the ozone depletion category, where the total burden is given by the air emissions from the aseptic carton converting plant, in particular by emissions of ozone depleting substances resulting from CFC/HCFC/Halon leakages (0.49 mg of CFC-11 and Halon 1301 per 1 kg of Aseptic carton container; see Table 4 in the inventory). The halon 1301 is one of the substances characterized by the highest characterisation factor for the ozone depletion category (15.2 kg CFC-11 eq./kg substance; Fazio et al., 2018)

Finally, as regards the end of life, it should be noted the generally low contribution given by the collection of the container with the residual waste and its incineration. A significant benefit (negative sign) is seen only in the category of resource use-energy carriers, while a not negligible burden (positive sign) is observable in the freshwater ecotoxicity.

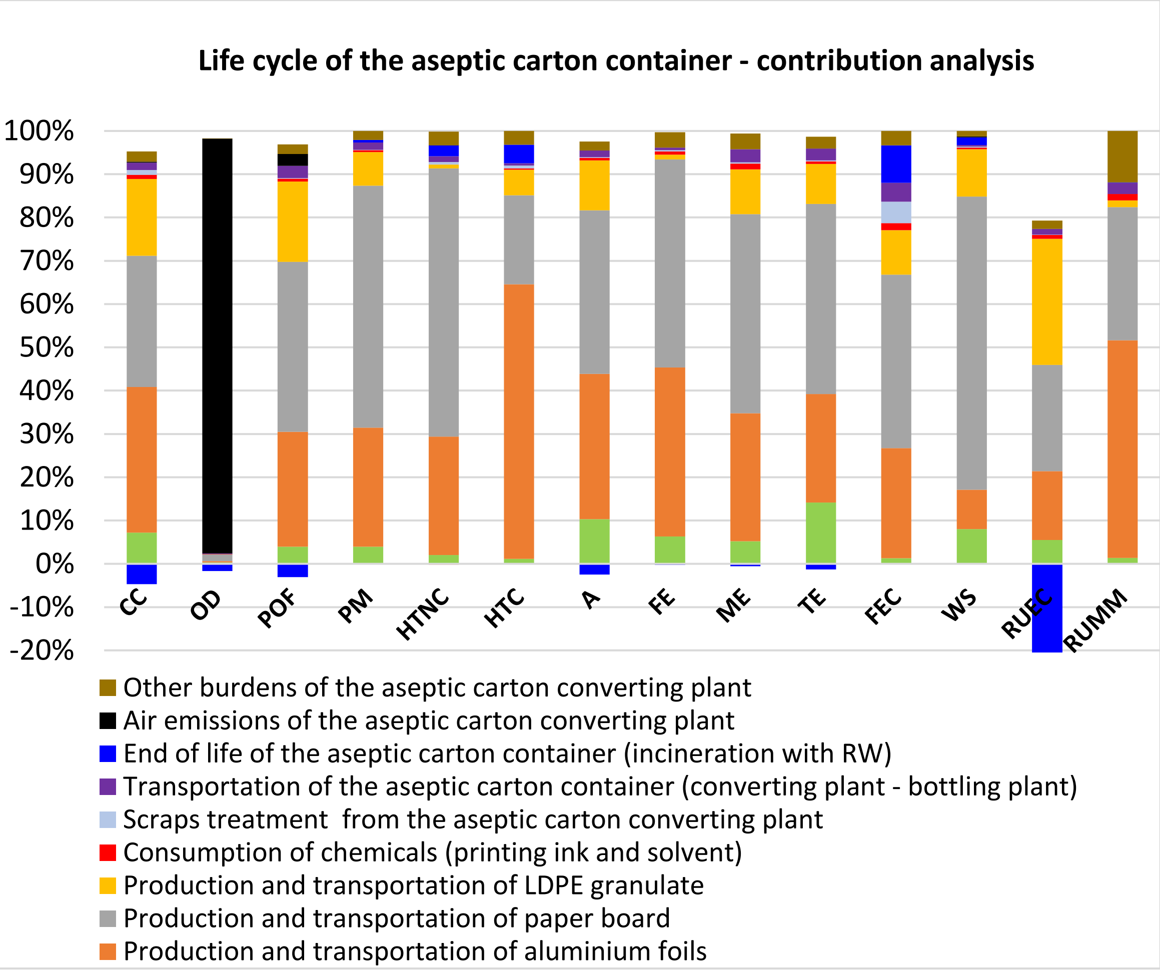


Figure 15. Percentage contribution of the different stages to the total impact of the life cycle of aseptic carton container, format 0.5 litres.

5.1.1 Analysis of Three Scenarios of End-of-Life of Aseptic Carton Container

As explained in Chapter 4.4 (inventory analysis), three different scenarios of end of life for the aseptic carton container were analysed:

- SCENARIO 1 - TREATMENT WITH THE RESIDUAL WASTE. The container is collected with the Residual Waste (RW) and sent to an incineration plant with energy recovery (the typical way of RW treatment in northern Italy);
- SCENARIO 2 - TREATMENT IN A CONVENTIONAL PAPER MILL. The container is collected with paper separated at source, sent to a paper sorting plant and then to a conventional paper mill for recycling;
- SCENARIO 3 - TREATMENT IN A DEDICATED PAPER MILL. The container is collected with paper separated at source, sent to a paper sorting plant and then recycled in a paper mill specialized in aseptic carton recovery.

The impacts associated only to the treatment of the aseptic carton waste (1 kg) in the different scenarios are calculated, analysed by contribution analysis, and compared.

Table 13 reports the potential impacts related to the treatment of 1 kg of aseptic carton for each scenario. At a first glance, it is possible to notice that scenario 3 is dominated by negative values (meaning a benefit for the environment), while scenario 2 and 3 are more balanced between benefits and burdens. Below each scenario is analysed in detail. At the end of the paragraph, it is then analysed how the end of life of the aseptic carton container can influence the overall impacts of the water distribution system.

Table 13. Value of potential impacts associated to the treatment of 1 kg of aseptic carton waste in each scenario.

Impact indicator		SCENARIO 1	SCENARIO 2	SCENARIO 3
CC	kg CO2 eq	-1.32E-01	5.43E-03	-1.60E-01
OD	kg CFC11 eq	-1.38E-07	-9.57E-08	-8.97E-08
POF	kg NMVOC eq	-3.44E-04	-1.52E-04	-1.60E-03
PM	disease inc.	1.65E-09	1.48E-08	1.42E-09

HTNC	CTUh	1.43E-08	-1.49E-09	-7.18E-08
HTC	CTUh	3.30E-09	2.37E-09	-2.72E-09
A	mol H+ eq	-4.41E-04	-3.51E-04	-3.37E-03
FE	kg P eq	-2.24E-06	-1.66E-04	-5.13E-04
ME	kg N eq	-1.95E-05	2.44E-05	-6.01E-04
TE	mol N eq	-5.34E-04	9.83E-04	-7.60E-03
FEC	CTUe	2.49E-01	2.65E-01	6.89E-02
WS	m3 depriv.	2.67E-02	7.56E-02	-9.71E-02
RUEC	MJ	-1.11E+01	-1.02E+01	-1.44E+01
RUMM	kg Sb eq	1.05E-09	7.08E-07	1.63E-07

Scenario 1: collection and treatment with the residual waste

Figure 16 reports the potential impacts associated to the management of 1 kg of aseptic carton together with the residual waste and the relative contribution analysis divided between the following steps:

1. RW door-to-door collection and transportation from the municipal deposit to the WTE plant;
2. burdens of incineration, i.e. consumption of chemicals, air emissions and treatment of solid residues associated to the combustion of paper (75% of the waste), aluminium (5%), and polyethylene (20%);
3. recovery of electricity and thermal energy from the incineration (avoided production of energy from fossil fuels).

	Impact category	Total impact (1 kg of waste)
CC	kg CO_2 eq.	-1.32E-01
OD	kg CFC11 eq.	-1.38E-07
POF	kg NMVOC eq.	-3.44E-04
PM	disease inc.	1.65E-09
HTNC	CTUh	1.43E-08
HTC	CTUh	3.30E-09
A	mol H^+ eq.	-4.41E-04
FE	kg P eq.	-2.24E-06
ME	kg N eq.	-1.95E-05
TE	mol N eq.	-5.34E-04
FEC	CTUe	2.49E-01
WS	m^3 depriv.	2.67E-02
RUEC	MJ	-1.11E+01
RUMM	kg Sb eq.	1.05E-09

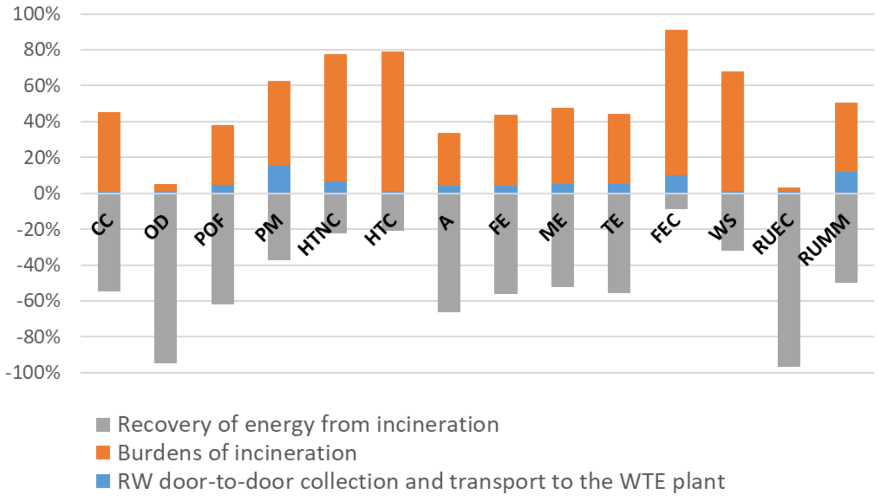


Figure 16. Potential impacts associated to the treatment of 1 kg of aseptic carton waste with the RW and relative contribution analysis.

We can observe that this way of waste treatment results in an overall environmental benefit for 8 out of 14 categories (the impact has a negative sign).

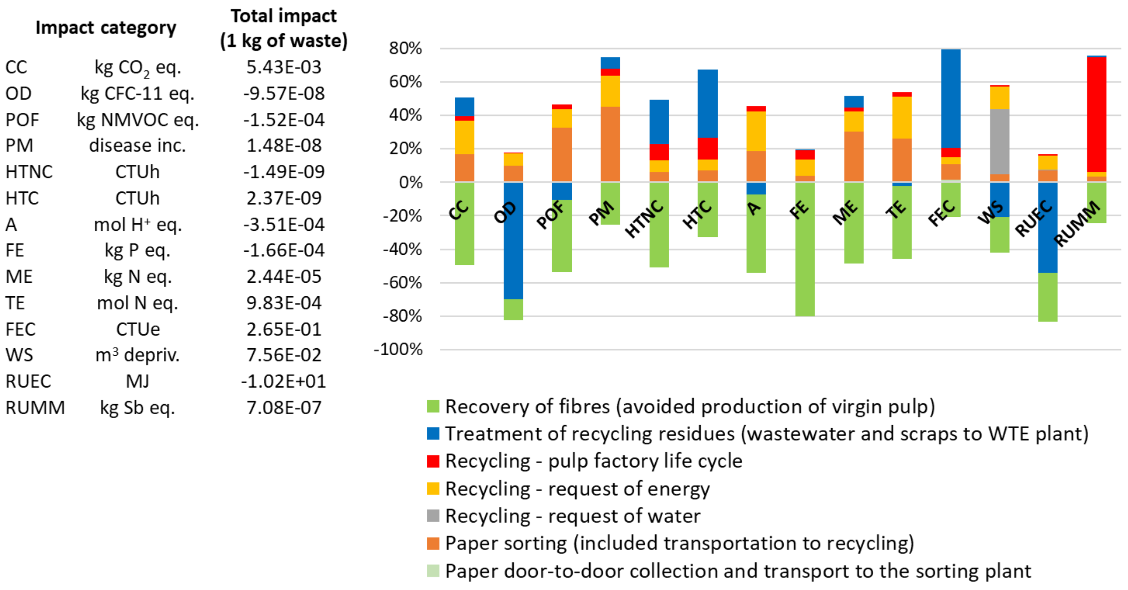
The contribution of the door-to-door collection and transport to the WTE plant is negligible with respect to the other two phases. The contribution of incineration burdens is always higher than 29% except for the categories of ozone depletion and resource use-energy carriers. In particular, in the indicator of freshwater ecotoxicity it is over 80%.

In the impact categories of ozone depletion and resource use-energy carriers, the contribution related to the avoided production of energy is more than 94% and it is mainly associated to the recovery of electricity.

Scenario 2: treatment in a conventional paper mill

In the second scenario, post-consumer aseptic carton containers are collected together with paper separated at the source, transported to a paper sorting plant and then to a conventional paper mill. The output flows of the recycling process are recovered fibres (35% of the input paper from Aseptic carton) and a wet residue composed of aluminium, plastic and fibres not recovered, destined to a WTE plant. Figure 17 reports the potential impacts associated to the management of 1 kg of aseptic carton waste and the relative contribution analysis subdivided among the following main process stages:

1. Paper door-to-door collection and transport to the sorting plant;
2. Paper sorting operations (consumption of electricity, diesel and lubricating oil) and transport to the paper recycling plant;
3. Recycling burdens in terms of energy consumption;
4. Recycling burdens in terms of water request;
5. Recycling burdens in terms of pulp factory life cycle;
6. Treatment of the wastewater and of the solid residues in a WTE plant;
7. Recycling benefits in terms of recovery of paper fibres (avoided production of virgin thermomechanical pulp).



Impact category		Total impact (1 kg of waste)
CC	kg CO$_2$ eq.	5.43E-03
OD	kg CFC-11 eq.	-9.57E-08
POF	kg NMVOC eq.	-1.52E-04
PM	disease inc.	1.48E-08
HTNC	CTUh	-1.49E-09
HTC	CTUh	2.37E-09
A	mol H$^+$ eq.	-3.51E-04
FE	kg P eq.	-1.66E-04
ME	kg N eq.	2.44E-05
TE	mol N eq.	9.83E-04
FEC	CTUe	2.65E-01
WS	m^3 depriv.	7.56E-02
RUEC	MJ	-1.02E+01
RUMM	kg Sb eq.	7.08E-07

Figure 17. Value of potential impacts associated to the recovery of 1 kg of aseptic carton waste in a conventional paper mill and relative contribution analysis.

In 6 out of 14 impact categories (OD/POF/HT_{NC}/A/FE/RU_{EC}), this scenario implies an overall benefit on the environment (impact with a negative sign). The benefit is always associated to the recovery of fibres with the avoided production of virgin pulp except for the categories of ozone depletion and resource use-energy carriers. In these indicators, the environmental advantage is related to the incineration of recycling residues in a WTE plant with the recovery of energy due to their lower heating value (10.9 kJ/kg residue).

In the other remaining 8 impact categories, a positive sign of the indicator is observable. Depending on the analysed impact category, impacts are due to energy consumption in the recycling and burdens of the sorting process (climate change, particulate matter, marine and terrestrial eutrophication), to the disposal of recycling residues (freshwater ecotoxicity and cancer human toxicity), to the water consumption by the pulper (water scarcity), and to the life cycle of the pulp factory (resource use, minerals & metals).

Scenario 3: treatment in a dedicated paper mill

In the third scenario, post-consumer aseptic carton containers are separately collected together with paper, transported to a sorting plant, and finally sent to a paper mill specifically dedicated to Aseptic carton recycling.

For this recycling process, it was not possible to acquire primary inventory data by the Italian companies involved in the sector because of confidentiality reasons. For this reason, the recovery rate of the cellulose from the aseptic packaging was assumed equal to 90% as indicated in Xie et al. (2013). Accordingly, the composition of the residue sent to incineration and its lower heating value were re-calculated, while in this part of analysis the recycling consumption (energy and water) were maintained the same of a conventional paper mill in absence of other indications. Then, in the sensitivity analysis (Paragraph 5.2) the request of water and energy for recycling in a dedicated paper mill will be changed. Impacts of this scenario of management (Figure 18) should then be considered only as preliminary results.

Impact category		Total impact (1 kg of waste)
CC	kg CO_2 eq.	-1.60E-01
OD	kg CFC11 eq.	-8.97E-08
POF	kg NMVOC eq.	-1.60E-03
PM	disease inc.	1.42E-09
HTNC	CTUh	-7.18E-08
HTC	CTUh	-2.72E-09
A	mol H^+ eq.	-3.37E-03
FE	kg P eq.	-5.13E-04
ME	kg N eq.	-6.01E-04
TE	mol N eq.	-7.60E-03
FEC	CTUe	6.89E-02
WS	m^3 depriv.	-9.71E-02
RUEC	MJ	-1.44E+01
RUMM	kg Sb eq.	1.63E-07

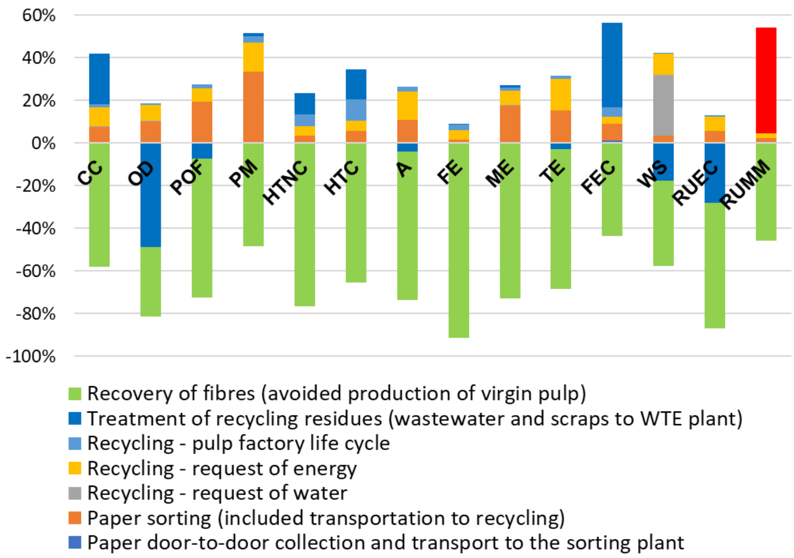


Figure 18. Value of potential impacts associated to the recovery of 1 kg of aseptic carton waste in a dedicated paper mill and relative contribution analysis.

Under the assumption of recovering 90% of the fibres, the aseptic carton collection with paper and its recovery in a dedicated paper mill shows an overall benefit in all the analysed impact categories except for three indicators (particulate matter, freshwater ecotoxicity, and resources use-minerals & metals). The recovery of fibres and the consequent avoided production of thermomechanical pulp shows a contribution higher than 30% in all the impact categories and in seven categories it is even over 60% (Figure 18).

The treatment of residues in a WTE plant with the production of heat and electricity shows a benefit higher than 20% in the resource use-energy carriers and about 50% in the ozone depletion.

5.1.2 Comparison among the Different Scenarios of Aseptic Carton Waste Management

Once calculated and analysed the impact results for each scenario, they were compared to evaluate the best solution of waste management (Figure 19). The comparison was carried out based on the same functional unit (*the management of 1 kg of waste*), including collection, possible sorting and recycling/energy recovery. Impact differences lower than 10% were arbitrarily assumed not significant due to uncertainties in the LCA modelling.

The third scenario, i.e. the recovery of aseptic carton in a dedicated paper mill, results the best solution of waste management for 12 out of 14 categories (all indicators except for ozone depletion and resource use, minerals & metals). On the contrary, the treatment in a conventional paper mill (Scenario 2) results the worst option in 8 out of 14 impact indicators (CC/POF/A/ME/TE/WS/PM/RU_{MM}). It should be noted that incineration with RW (scenario 1) is the worst option for both impact categories related to human toxicity.

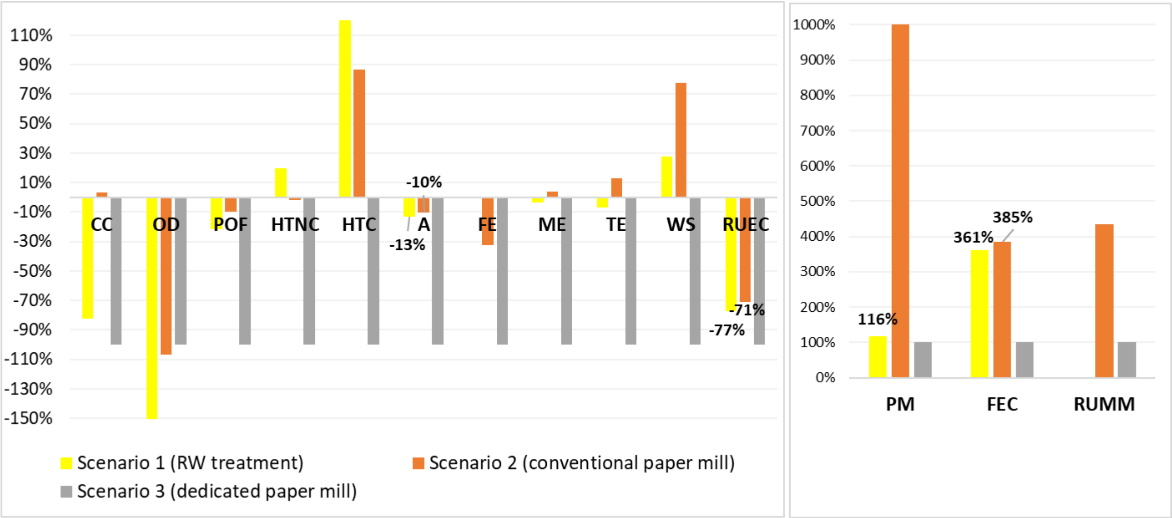


Figure 19. Comparison between the impacts associated to the different scenarios of aseptic carton waste management (1 kg). In the graph, the impact of Scenario 3 is put at 100%.

Considering the good performance of Scenario 3, its influence on the impacts of the water distribution system was analysed. The water distribution system with the incineration of 100% post-consumer aseptic carton containers was compared to the same distribution system were aseptic carton containers in their end of life are collected with paper and recycled in a conventional and in a dedicated plant (Figure 20).

In general terms, we can conclude that the end of life of the aseptic carton container does not significantly influence the overall impacts of the water distribution system. An impact variation higher than 10% is visible only in the impact category of freshwater eutrophication.

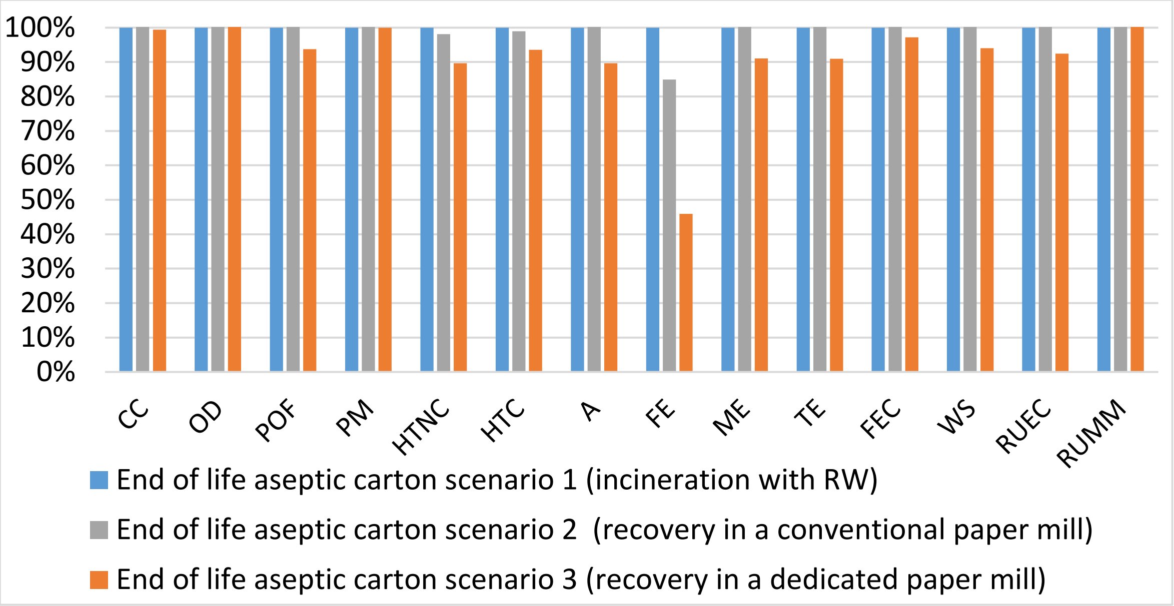


Figure 20. Comparison between the impacts of the water distribution system in 0.5L aseptic carton containers subjected to different ways of waste management. In the graph, the impact of the scenario 1 where post-consumer aseptic carton is sent to incineration is put at 100%.

5.2 Sensitivity Analysis

In this study, the most difficult part was data collection for Scenario 3. Dedicated paper mills, major companies for aseptic carton production and companies that use the residues of dedicated paper mill have been contacted but no quantitative data has been provided us because they are part of company's know-how. Also in literature, data about dedicated paper mills are not available. As previously mentioned, scenario 3 was examined assuming the same data as for scenario 2, except for the percentage of thermomechanical pulp recovered and for the distance between the paper sorting plant and the dedicated paper mill. This is not entirely true, because energy and water consumption of a dedicated paper mill might differ with respect to those of a conventional paper mill. That's why a sensitivity analysis on water and energy consumption was performed in order to check their influence on the results.

According to Paragraph 5.1.2, the best solution is scenario 3 (treatment in a dedicated paper mill) and the worst is scenario 2 (treatment in a conventional paper mill). In this sensitivity analysis, scenario 2 is not considered, because the differences with the other two scenarios are considerable, so it is clearly the worst scenario. So, starting from scenario 3 (calculated with water and energy consumption of a conventional paper mill), in this analysis the request of water and energy of a dedicated paper mill are arbitrarily increased as far as scenario 1 becomes better than scenario 3.

5.2.3 Sensitivity to the water consumption

Starting from scenario 3, the request of water is increased n times and the impact categories are recalculated (table 14). Then, the results are compared with scenario 1. As shown in figure 21, in 9 out of 14 categories (POF, HTNC, HTC, A, FE, ME, TE, FEC, RU_{EC}) scenario 3 results the best scenario even if the request of water of a dedicated paper mill is 30 times higher than a conventional paper mill. For ozone depletion and resource use, minerals & metals, incineration (scenario 1) is always the best solution. For water scarcity, the incineration is the best scenario if the request of water of a dedicated paper mill is greater than twice of a conventional paper mill.

At the end of this part of sensitivity analysis, it is possible to affirm that for water consumption the dedicated paper mill is the best scenario. So, the results of sensitivity analysis depend only on the request of energy.

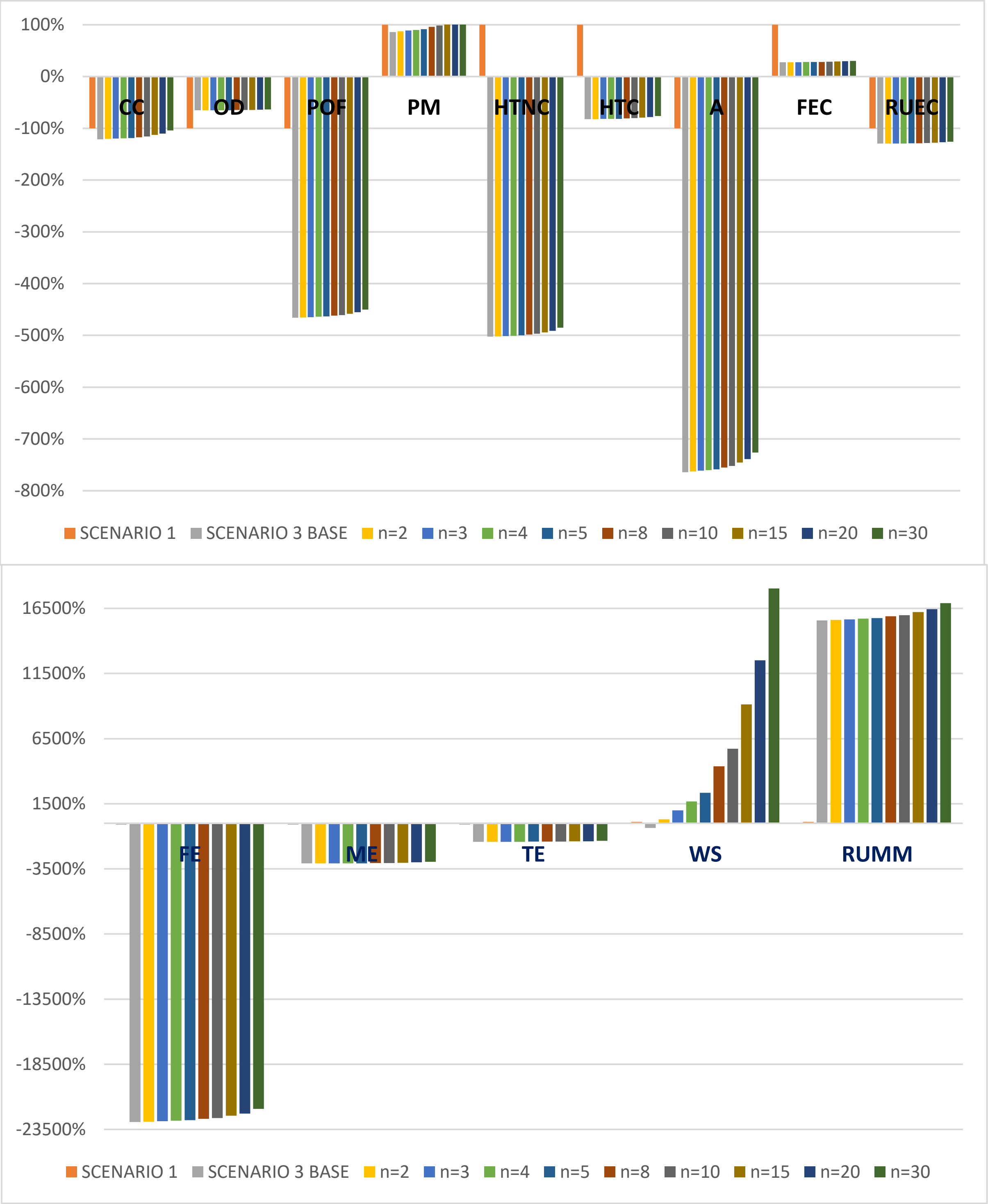


Figure 21. Comparison between the impacts associated to the different request of water of aseptic carton waste management (1 kg) in a dedicated paper mill. In the graph, the impact of Scenario 1 is set equal to 100%.

Table 14. Value of potential impacts associated to the treatment of 1 kg of aseptic carton waste in a dedicated paper mill by varying n times the request of water .

REQUEST OF WATER										
	SCENARIO 3	n=2	n=3	n=4	n=5	n=8	n=10	n=15	n=20	n=30
CC	-1.60E-01	-1.59E-01	-1.58E-01	-1.57E-01	-1.57E-01	-1.54E-01	-1.53E-01	-1.49E-01	-1.45E-01	-1.37E-01
OD	-8.97E-08	-8.96E-08	-8.96E-08	-8.95E-08	-8.94E-08	-8.93E-08	-8.91E-08	-8.89E-08	-8.86E-08	-8.80E-08
POF	-1.60E-03	-1.60E-03	-1.60E-03	-1.60E-03	-1.59E-03	-1.59E-03	-1.58E-03	-1.58E-03	-1.57E-03	-1.55E-03
PM	1.42E-09	1.44E-09	1.46E-09	1.49E-09	1.51E-09	1.58E-09	1.63E-09	1.74E-09	1.86E-09	2.09E-09
HTNC	-7.18E-08	-7.17E-08	-7.16E-08	-7.15E-08	-7.14E-08	-7.12E-08	-7.10E-08	-7.06E-08	-7.01E-08	-6.93E-08
HTC	-2.72E-09	-2.71E-09	-2.71E-09	-2.70E-09	-2.69E-09	-2.67E-09	-2.65E-09	-2.62E-09	-2.58E-09	-2.51E-09
A	-3.37E-03	-3.36E-03	-3.36E-03	-3.35E-03	-3.34E-03	-3.33E-03	-3.32E-03	-3.29E-03	-3.26E-03	-3.20E-03
FE	-5.13E-04	-5.12E-04	-5.12E-04	-5.11E-04	-5.10E-04	-5.08E-04	-5.06E-04	-5.02E-04	-4.98E-04	-4.91E-04
ME	-6.01E-04	-6.00E-04	-5.99E-04	-5.98E-04	-5.97E-04	-5.95E-04	-5.93E-04	-5.89E-04	-5.85E-04	-5.77E-04
TE	-7.60E-03	-7.58E-03	-7.57E-03	-7.56E-03	-7.55E-03	-7.51E-03	-7.48E-03	-7.42E-03	-7.35E-03	-7.22E-03
FEC	6.89E-02	6.91E-02	6.93E-02	6.96E-02	6.98E-02	7.05E-02	7.10E-02	7.21E-02	7.33E-02	7.56E-02
WS	-9.71E-02	8.36E-02	2.64E-01	4.45E-01	6.25E-01	1.17E+00	1.53E+00	2.43E+00	3.33E+00	5.14E+00
RUEC	-1.44E+01	-1.44E+01	-1.44E+01	-1.43E+01	-1.43E+01	-1.43E+01	-1.42E+01	-1.42E+01	-1.41E+01	-1.39E+01
RUMM	1.63E-07	1.63E-07	1.64E-07	1.64E-07	1.65E-07	1.66E-07	1.67E-07	1.69E-07	1.72E-07	1.77E-07

5.2.4 Sensitivity to the energy consumption

As in the previous analysis, starting from scenario 3, the request of energy is increased n times and impact categories are recalculated (table 15). Then, the results are compared with scenario 1. As shown in figure 22, for climate change and particulate matter, incineration is the best scenario if the request of energy of a dedicated paper mill is twice that of a conventional paper mill. For ozone depletion and resource use, minerals & metals, incineration is always the best scenario. For photochemical ozone formation and marine eutrophication, scenario 1 is better than scenario 3 if the request of energy is eight times higher than that of a conventional paper mill. For non-cancer human health effects and ecotoxicity freshwater, incineration is the best solution if the energy consumption of a dedicated paper mill is fifteen times higher than a conventional one. For cancer human health effects, incineration becomes the best scenario if energy requested by dedicated paper mill is twenty times of conventional paper mill. For terrestrial and freshwater acidification and resource use, energy carriers, scenario 1 is the best one for energy consumption equal to five times of a conventional paper mill. For freshwater eutrophication, dedicated paper mill is inconvenient for energy consumption equal to thirty times of a conventional paper mill. For terrestrial eutrophication, incineration is the best scenario if the request of energy of a dedicated paper mill is four times of a conventional paper mill. For water scarcity, scenario 1 is better than scenario 3 if the request of energy is three times of a conventional paper mill.

Combining these results, it’s possible to conclude that as end-of-life of aseptic carton container, dedicated paper mill is the best scenario for request of energy up to four times of a conventional paper mill. If the energy consumption is five times or more, the best scenario for end-of-life of aseptic carton container is the incineration.

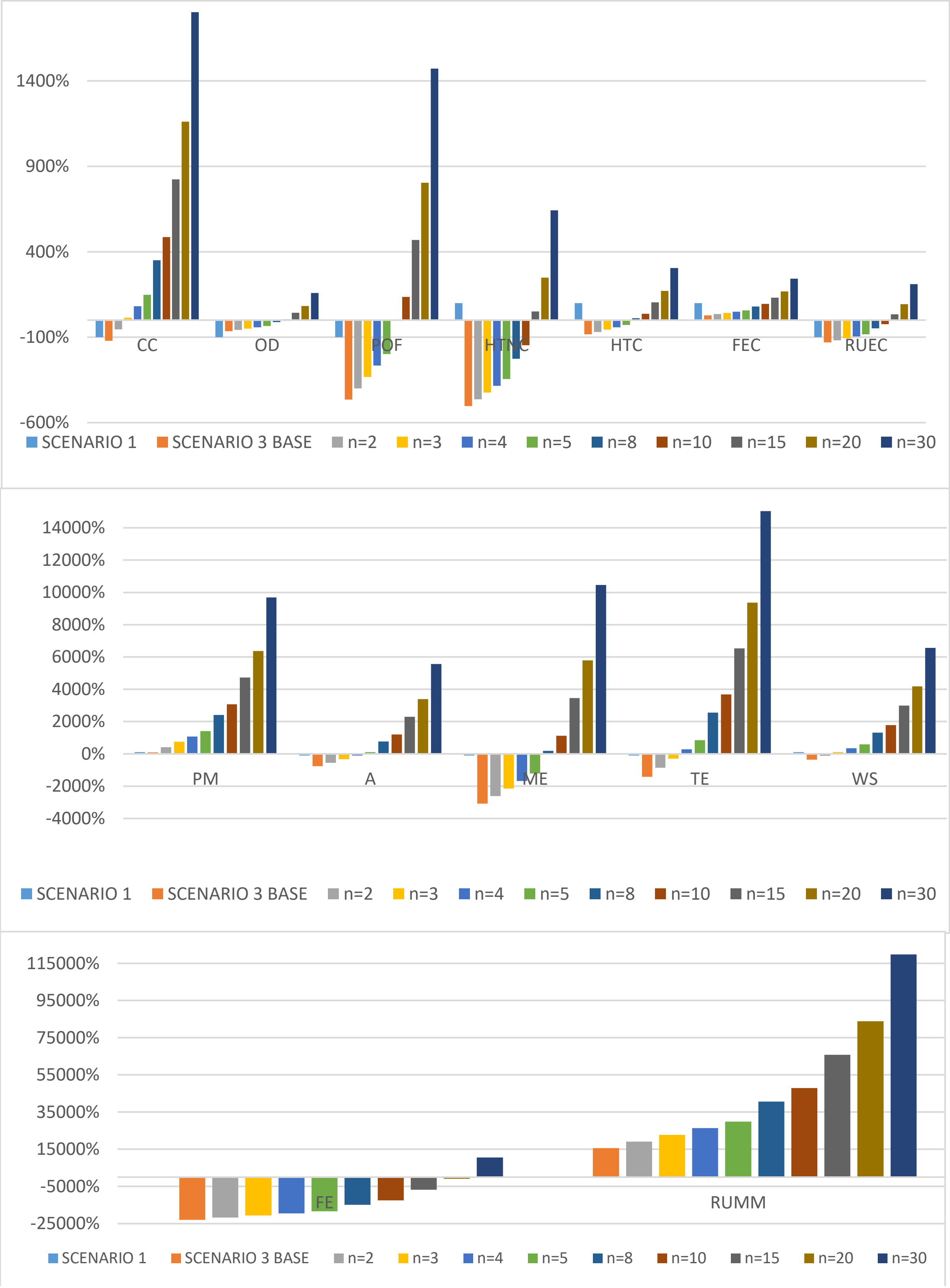


Figure 22. Comparison between the impacts associated to the different request of energy of aseptic carton waste management (1 kg) in a dedicated paper mill. In the graph, the impact of Scenario 1 is set equal to 100%.

Table 15. Value of potential impacts associated to the treatment of 1 kg of aseptic carton waste in a dedicated paper mill varying the request of energy of n times.

REQUEST OF ENERGY										
	SCENARIO 3	n=2	n=3	n=4	n=5	n=8	n=10	n=15	n=20	n=30
CC	-1.60E-01	-7.07E-02	1.83E-02	1.07E-01	1.96E-01	4.63E-01	6.41E-01	1.09E+00	1.53E+00	2.42E+00
OD	-8.97E-08	-7.90E-08	-6.83E-08	-5.76E-08	-4.70E-08	-1.49E-08	6.44E-09	5.98E-08	1.13E-07	2.20E-07
POF	-1.60E-03	-1.37E-03	-1.14E-03	-9.12E-04	-6.82E-04	7.22E-06	4.67E-04	1.62E-03	2.77E-03	5.06E-03
PM	1.42E-09	6.87E-09	1.23E-08	1.78E-08	2.32E-08	3.96E-08	5.05E-08	7.78E-08	1.05E-07	1.60E-07
HTNC	-7.18E-08	-6.61E-08	-6.05E-08	-5.48E-08	-4.92E-08	-3.23E-08	-2.10E-08	7.26E-09	3.55E-08	9.19E-08
HTC	-2.72E-09	-2.28E-09	-1.84E-09	-1.40E-09	-9.57E-10	3.65E-10	1.25E-09	3.45E-09	5.65E-09	1.01E-08
A	-3.37E-03	-2.41E-03	-1.44E-03	-4.81E-04	4.82E-04	3.37E-03	5.29E-03	1.01E-02	1.49E-02	2.45E-02
FE	-5.13E-04	-4.87E-04	-4.61E-04	-4.35E-04	-4.10E-04	-3.32E-04	-2.80E-04	-1.51E-04	-2.11E-05	2.38E-04
ME	-6.01E-04	-5.10E-04	-4.19E-04	-3.28E-04	-2.37E-04	3.59E-05	2.18E-04	6.72E-04	1.13E-03	2.04E-03
TE	-7.60E-03	-4.57E-03	-1.53E-03	1.50E-03	4.53E-03	1.36E-02	1.97E-02	3.48E-02	5.00E-02	8.03E-02
FEC	6.89E-02	8.73E-02	1.06E-01	1.24E-01	1.43E-01	1.98E-01	2.35E-01	3.27E-01	4.19E-01	6.03E-01
WS	-9.71E-02	-3.33E-02	3.04E-02	9.41E-02	1.58E-01	3.49E-01	4.76E-01	7.95E-01	1.11E+00	1.75E+00
RUEC	-1.44E+01	-1.31E+01	-1.18E+01	-1.05E+01	-9.19E+00	-5.29E+00	-2.69E+00	3.82E+00	1.03E+01	2.33E+01
RUMM	1.63E-07	2.00E-07	2.38E-07	2.75E-07	3.13E-07	4.26E-07	5.01E-07	6.88E-07	8.76E-07	1.25E-06

Chapter 6

Life Cycle Assessment Comparison of Bottled Water: One-Way Aseptic Carton Bottle vs. One-Way PET Bottles

In this chapter a comparison between one-way aseptic carton bottle and the alternative system based on PET bottles is reported. The environmental performance of this system was studied in another work of the AWARE group, a master thesis in environmental engineering (Grisales, 2020). A summary of the study is reported in the following sections.

6.1 Description of the PET Bottles Distribution System

The distribution system is based on Polyethylene Terephthalate (PET) bottles, including a High-Density Polyethylene (HDPE) cap and an informative label, made of paper or plastic. Since this study focuses on the water delivered to the Horeca sector (e.g., restaurants and cafés), the 0.5-liter bottles are analysed considering that this is the most used format for out-of-home consumption. Table 16 reports the average weight of the packaging components according to the collected sample in retail stores of Milan.

Table 16. Main characteristics of the 0.5 litres PET bottle (Grisales, 2020).

Component of packaging	Material	Mass (g/bottle)
Bottle	PET	12.72
Cap	HDPE	2.12
Label	Polypropylene (PP) - 86% of the sample	0.31
	Paper - 14% of the sample	0.73

In the analysed water distribution system (Figure 21), the components of the bottle are manufactured in dedicated plants and then transported to the reference bottling facility. Here, preforms are blown to generate the bottles, that are filled, capped, labelled, arranged in groups of six each one and finally wrapped with a LDPE heat-shrink film. One pack of six bottles will be defined as bundle. Full bottles are then transported by road from the bottling plant to a local distributor in Northern Italy (300 km, Annex 2), which delivers them to the final user (30 km, ACI 2019). After the water consumption, bottles are discarded by the user in the municipal waste and collected and treated according to the urban waste management system in Northern Italy. In particular, 55% of the bottles are separately collected with plastic and sent to recycling, while the remaining 45% are discarded with the residual waste and incinerated in a Waste-to-Energy plant (Bevitalia, 2019).

6.2 Functional Unit

The function of the analysed system is to provide a certain volume of mineral water to the final user by 0.5-liter PET bottles. Like in this study, the Functional Unit (FU) is assumed as *the delivery of 100 litres of mineral water (corresponding to 200 analysed bottles)*.

6.3 System Boundary

The system boundary (Figure 23) includes:

- the manufacturing of the primary and secondary packages and the relative transportation to the bottling plant;
- the operations at the bottling plant (blowing of PET preforms, filling, capping, labelling, and packing into bundles);
- the distribution of PET water bottles (transportation from the bottling plant to the local distributor and then to the final user);

- the end of life of the primary and secondary packages, i.e. collection and waste treatment in dedicated facilities. In this stage, cases of multi-functionality related to the avoided productions due to the recovery of energy (incineration in a WTE plant) and materials (process of PET recycling) were solved by expanding the system boundary according to Finnveden et al. (2009).

Due to the lack of data, the life cycle of tertiary packaging for the transportation was not included. Moreover, also the extraction of 100 litres of mineral water was excluded since the focus of the study is the analysis of different packaging distribution systems all providing the same amount of water.

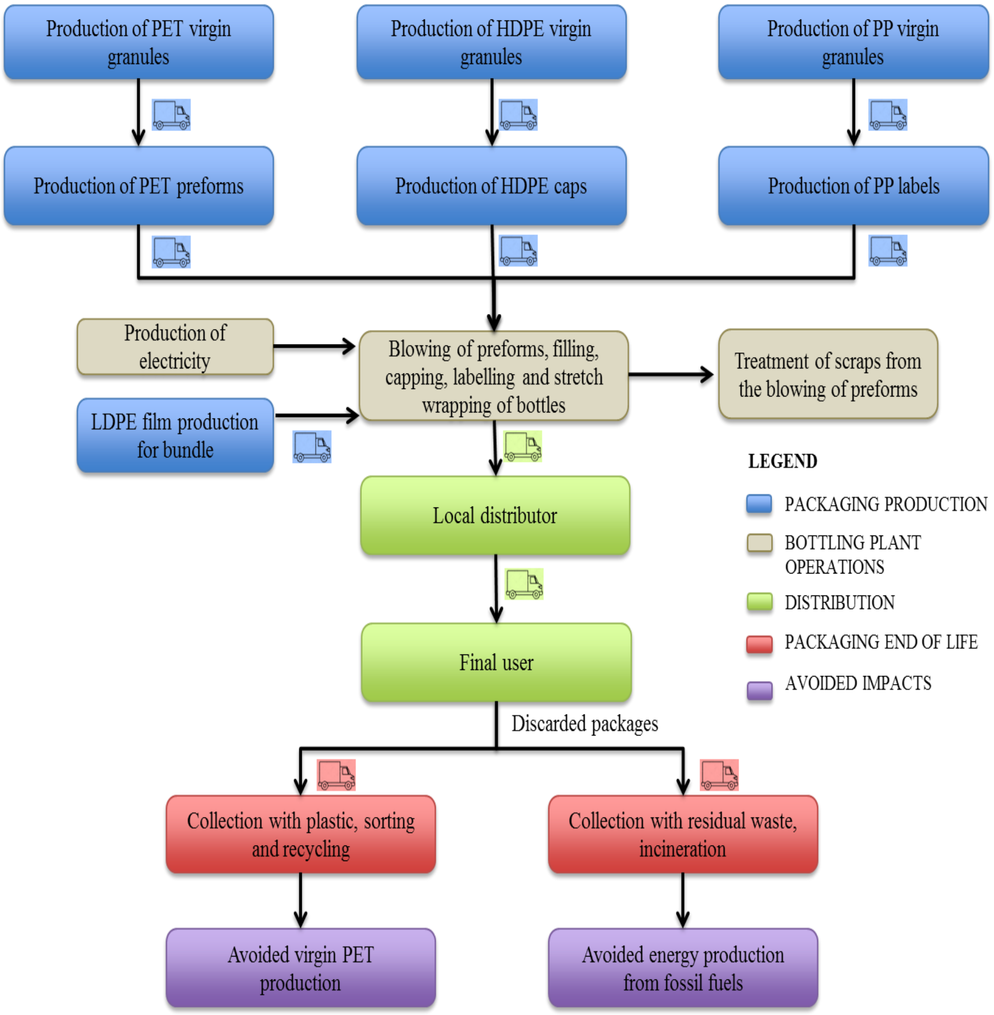


Figure 23. Analysed system of PET bottles with the relative system boundary (Grisales, 2020).

6.4 Data Quality

The geographical scope of the study is Northern Italy and the collected data are related to the years 2017-2019. The foreground system was mainly described with primary data except for the bottling plant operations for which literature data were used (Amienyo et al., 2013)..

In particular, primary data about the involved packages (mass and material) were gathered by collecting samples in different retail stores in the city of Milan. Data concerning the travelled distances and the ways of transport in the distribution stage were derived according to the Italian market of mineral water. In detail, Ferrarelle SpA, which is one of the first five-bottled water companies in Italy (Bevitalia, 2019), provided some primary data on this stage. Finally, as regards the packaging end of life, inventory data from waste treatment facilities in the northern Italy collected in previous works of the AWARE group (Grosso et al., 2012, Rigamonti et al., 2010) were used. For the processes of the background system (such as electricity production or plastic granulates manufacturing), data from the ecoinvent 3.5 database (ecoinvent, 2018), *allocation cut-off by classification* approach were derived.

6.4.1 Selected Indicators

Like for this study, 14 impact categories from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018) were selected.

6.5 Results of the comparison

In figure 24, the results of LCA of PET bottle and LCA of aseptic carton bottle are expressed in a single graph for the comparison.

For climate change and acidification, PET bottle and aseptic carton bottle are comparable. For ozone depletion, the difference between the two bottles is substantial: PET is clearly better than aseptic carton. For photochemical ozone formation, marine eutrophication and ecotoxicity freshwater, the difference between the two system is about 25% and again PET bottle is the best system. For particulate matter, cancer and non-cancer human health effects, the impact of PET system is about half that of aseptic carton. For terrestrial eutrophication and water scarcity, the difference between the two system is about 15%: for a few percentage points PET system is the better than aseptic carton. For freshwater eutrophication, the aseptic carton bottle is clearly better than the PET bottle. For resource use, both for energy carriers and for mineral and metals, the two alternatives are almost comparable, but for a few percentage points aseptic carton container results better.

In conclusion, for ten categories out of fourteen, PET bottle is better than aseptic carton bottle.

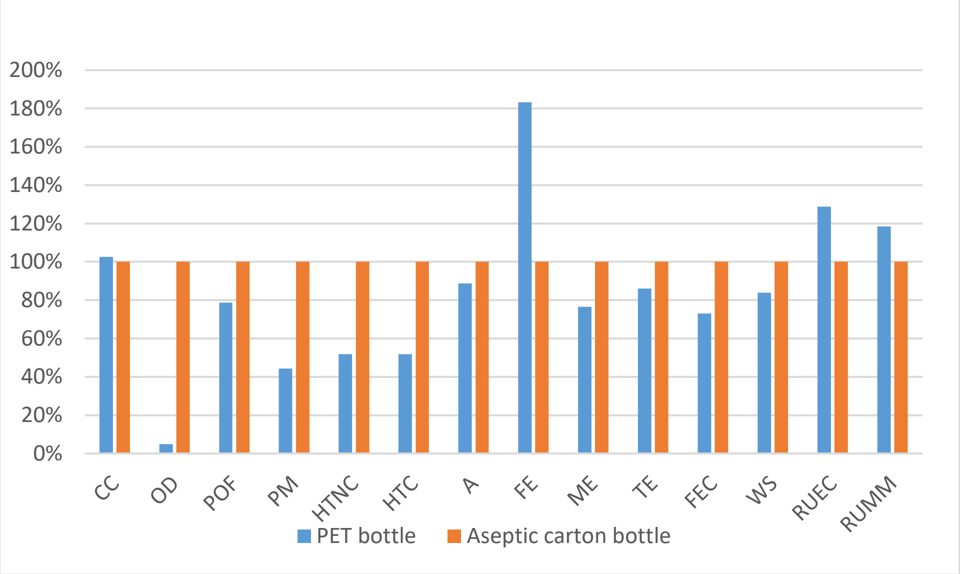


Figure 24. Comparison between PET bottle and aseptic carton bottle (scenario 3 as end-of-life of aseptic carton container) for each impact category. In the graph, the impact of aseptic carton bottle is put at 100%.

In particular, the LCA of PET bottles is divided into seven phases:

1. Life cycle of the PET bottle;
2. Life cycle of the HDPE cap;
3. Life cycle of the PP label;
4. Life cycle of the LDPE bundle;
5. Bottling plant operation;
6. Transportation from the bottling plant to the local distributor;
7. Transportation from the local distributor to the final user;

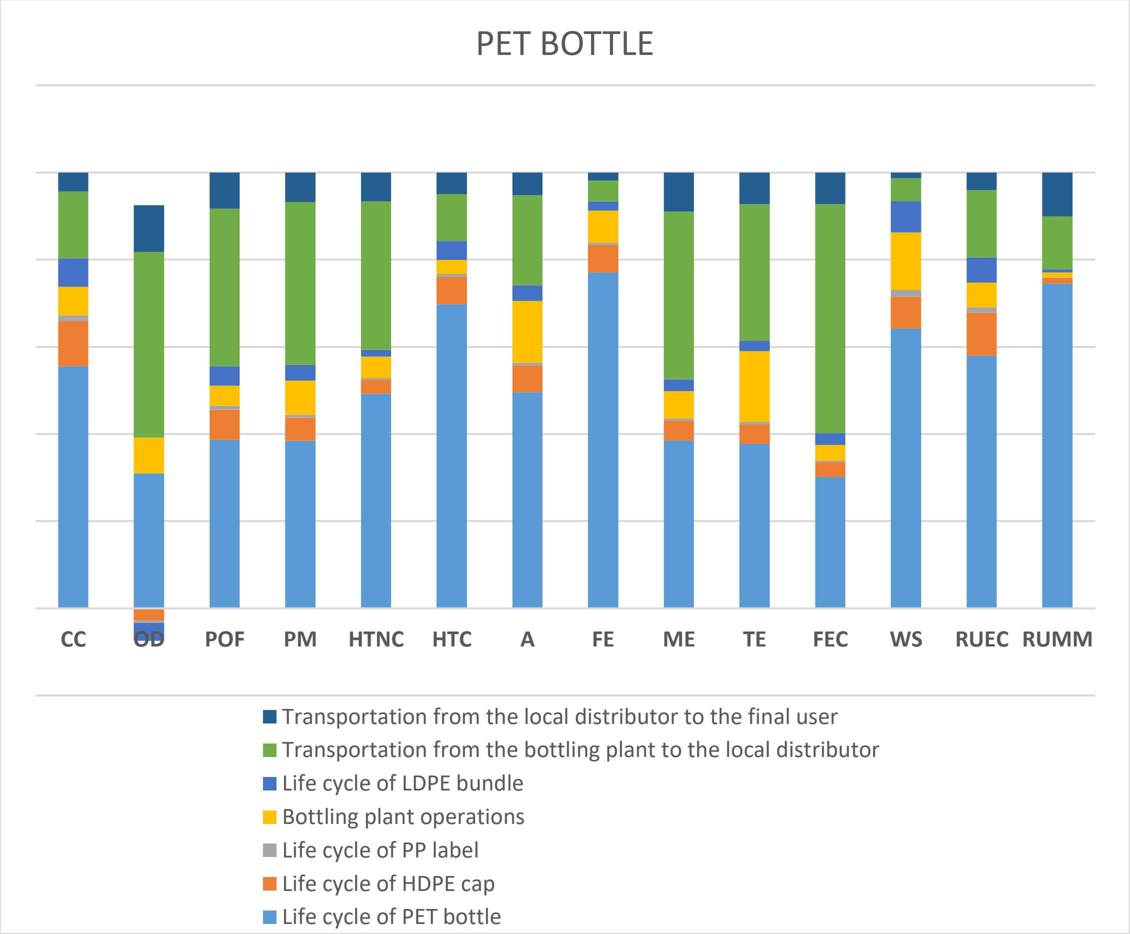


Figure 25. Percentage contribution of the different stages to the total impacts of the distribution system based on water PET bottles.

As shown in Figure 25, the life cycle of the bottle represents the most important contribution to the potential impact in all the analysed categories except for the ozone depletion and fresh water ecotoxicity indicators. Depending on the category, the contribution of this stage ranges from 30% to 77%.

Another important stage in terms of impacts is the transportation of the bottles from the bottling plant to the local distributor (300 km on average). Its contribution is higher than 30% in seven impact categories (ozone depletion, photochemical ozone formation, particulate matter, human toxicity non-cancer effects, freshwater ecotoxicity, marine and terrestrial eutrophication) and reaches 50% for the ozone depletion and freshwater ecotoxicity indicators. Also, the bottling plant operations show a non-negligible contribution (higher than 10%) in the impact categories of acidification (14%), terrestrial eutrophication (16%) and water scarcity (13%). The contribution of the other stages (life cycle of cap, label, bundle and the transportation from the local distributor to the final user) is generally contained within 10%.

In order to improve the results of this comparison in favour of aseptic carton, it is necessary to address the most impacting phases: life cycle of container and transportation of the bottles from the bottling plant to the local distributor.

In the life cycle of the container, the most important burdens are given by the production of aluminum foils and paper board and by their transportation to the converting plant. To improve these impact, recycled paper and secondary aluminum could be used, but this is forbidden, since only virgin materials are allowed for beverage packaging.

Regarding the transportation from the bottling plant to the local distributor, the comparison was made according to the same distribution distance of the water (300 km). When increasing the distribution distance for both systems, PET and aseptic carton become more and more comparable.

For a distribution distance of 500 km, PET system can be considered a better option for nine categories with respect of ten categories related to 300 km of distribution distance. As shown in Figure 26, for acidification, the two systems become comparable. B y furtherly increasing the distribution distance to 700 km (Figure 27) or even 900 km (Figure 28), the PET system remains the best options but now for eight categories. For terrestrial eutrophication, the two options become comparable. For the other categories, PET system is always the best option. The distribution distance could be increased further, and the two systems would become even more comparable, but since in this thesis the focus of the analysis is on the national distribution (maximum 900 km), PET system will always remain the best solution.

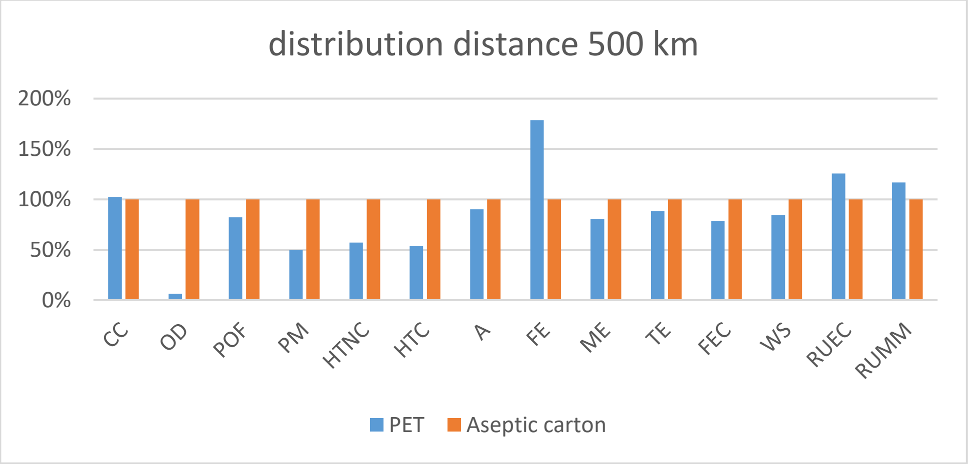


Figure 26. Comparison for a distribution distance equal to 500 km.

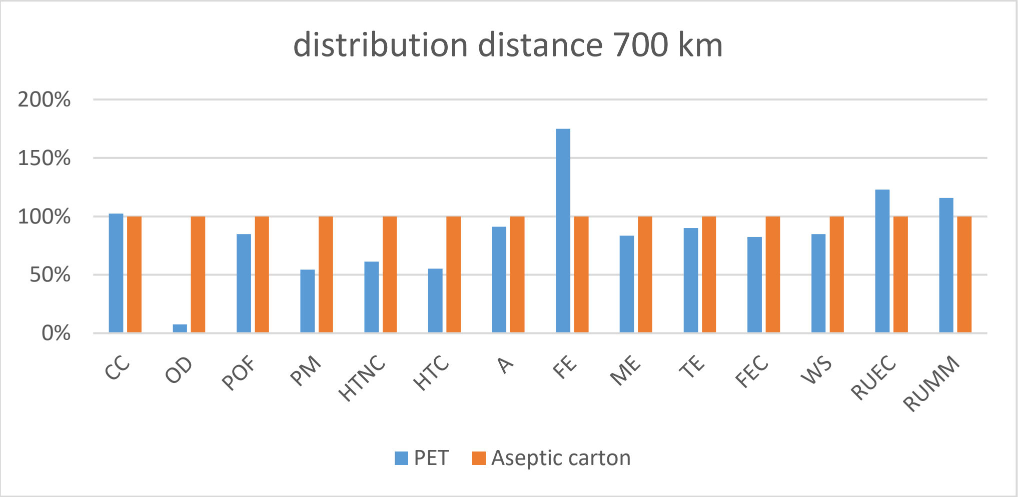


Figure 27. Comparison for a distribution distance equal to 700 km.

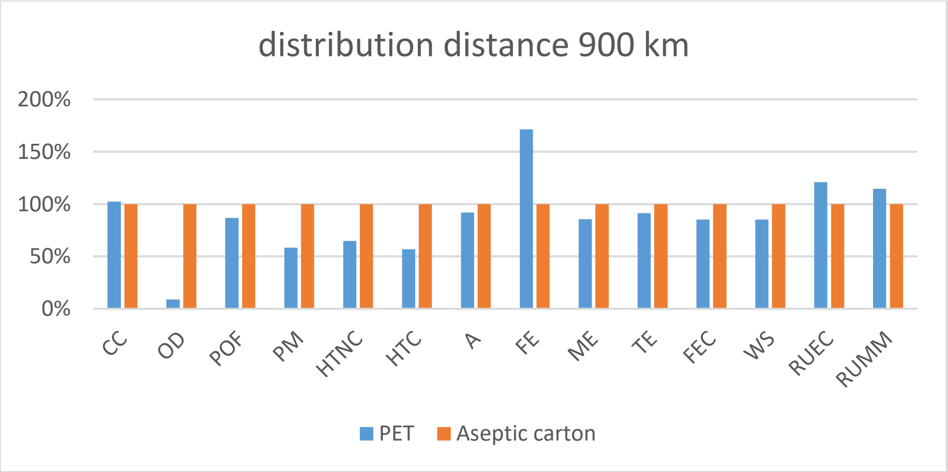


Figure 28. Comparison for a distribution distance equal to 900 km.

Chapter 7

Conclusions

This thesis has assessed the environmental and energy impacts generated from the aseptic carton bottles containers for water delivery throughout their life cycle in the context of northern Italy.

The life cycle perspective allowed to identify the most important burdens related to the analysed system and to provide the involved operators with recommendations for a better management.

In most of the impact categories, the burdens of the system are mainly associated to the life cycle of the bottle (45-97% of the overall impacts), in particular to the production and transportation of virgin paper boards and aluminum foils. Another stage with significant impact is the transportation of the containers from the bottling plant to the local distributor, showing a contribution higher than 15% in eight impact categories and reaching a maximum contribution of 37% in the freshwater ecotoxicity indicator.

In this study, three scenarios for the end of life management of the aseptic carton container are analysed: treatment with the residual waste, treatment in a conventional paper mill and treatment in a dedicated paper mill specifically adapted for processing this type of containers. The latter results the best solution of waste management for 12 out of 14 categories. On the contrary, the treatment in a conventional paper mill results the worst option in 8 out of 14 impact indicators. It should be noted that incineration together with the RW (scenario 1) is the worst option for both impact categories related to human toxicity. In general terms, we can conclude that the end of life of the aseptic carton container does not significantly influence the overall impacts of the water distribution system.

However, it must be considered that for the analysis of the third scenario no data were available in the literature and neither dedicated paper mills nor Tetra Pak have provided us with any data because they are part of the company's know-how. So in a first tentative we only changed the percentage of recovered thermomechanical pulp (increased to 90%) and the distance between sorting plant and dedicated paper mill (increased from 100 to 200 km, since only two dedicated paper mills are available in Italy), keeping all other data constant with respect to the conventional paper mill. This lack of data is the starting point for the sensitivity analysis. Water and energy consumption of dedicated paper mill are likely to be different from a conventional paper mill. So, starting from scenario 3 (calculated with water and energy consumption of a conventional paper mill), the request of water and energy of a dedicated paper mill are increased till to find the value (in terms of consumption) for which scenario 1 becomes better than scenario 3. We find that the results of the sensitivity analysis depend only on request of energy: even if the request of water of a dedicated paper mill is thirty times higher than that of a conventional paper mill, scenario 3 will remain better than scenario 1. From the energy consumption analysis, we obtain that the dedicated paper mill remains the best scenario up to four times increase of the request of energy. If the energy consumption is five times or more, the best scenario for end-of-life of aseptic carton container is the incineration.

The second part of this study was focused on the comparison between one-way aseptic carton containers and one-way PET bottles, in order to evaluate which system has a better environmental performance. The environmental performance of PET bottles was evaluated in another work of the AWARE group, a master thesis in environmental engineering (Grisales, 2020). As end-of-life of aseptic carton containers, we consider the best one derived from the sensitivity analysis, that is the third analysed scenario: advanced paper mill. For ten categories out of fourteen, the PET bottle results clearly better than the aseptic carton container. When increasing the distribution distance for both systems, PET and aseptic carton become more comparable, but considering the national distribution (up to 900 km) PET system will remain the best solution.

Annex 1

Avoided Production of Heat from a Domestic Gas Boiler

For the avoided production of thermal energy, the produced heat was assumed to be delivered to a district heating network, with a 10% loss for the distribution. The substituted technology was modelled as heat generated by a domestic gas boiler (power < 100 kW), with an 87% efficiency. The emission factors of this technology are reported in Table 17 Annex.1 while the avoided consumption of natural gas is equal to 28 l/MJ consumed (*Natural gas, low pressure {CH}| market for*).

Table 17. Air emission factors for the production of heat from a gas domestic boiler. Values are expressed per GJ of consumed natural gas.

Pollutant	**Emission factor**	**Source**	**Pollutant**	**Emission factor**	**Source**
CO	25 g	ISPRA (2018)	Hg	0.2 mg	ISPRA (2018)
N_2O	1 g		Ni	0.51 µg	EEA (2017)
CH_4	3 g		As	0.12 mg	
NO_X	31 g		Pb	1.5 µg	
VOC not methanogens	5 g		Cr	0.76 µg	
SO_2	0.3 g	EEA (2017)	Se	11 µg	
Total particulate (< 10 µm)	0.2 g	ISPRA (2018)	Cu	0.076 µg	
Fossil CO_2	57.2 kg		Benzene	2.2 µg	
Polycyclic aromatic hydrocarbons	9.9 mg	ANPA (2000)	Butane	1.8 g	ANPA (2000)
Dioxins and furans	1.5 ng	EEA (2017)	Ethane	2.7 g	
Cd	0.25 µg		Formaldehyde	0.9 g	
Pentane	1.8 g	ANPA (2000)	Propane	1.8 g	
Toluene	0.21 g		Zn	1.5 µg	EEA (2017)

Annex 2

Distance from the Bottling Plant to Milan

Table 18 reports the distance between the bottling plants of the different Italian brands of bottled water and the city of Milan. Only brands selling their products in Milan were included.

Table 18. Weight of primary packages from samples collected in Milan.

GROUP	**BRAND**	**Manufacture adress**	**Distance (Km.)**
SANPELLEGRINO S.p.A. NESTLÉ WATERS ITALIA	LEVISSIMA	Via Nazionale, 2/4/6 Fraz. Piazza 23030 Cepina Valdisotto SO	200
	LEVISSIMA (naturale)		200
	NESTLÈ VERA Fonte In Bosco	Via Valsugana, 5 35010 San Giorgio in Bosco PD	235
ACQUA MINERALE SAN BENEDETTO S.p.A.	SAN BENEDETTO	Via Kennedy, 65 30037 Scorzè VE	268
	SAN BENEDETTO Libera		268
FONTI DI VINADIO S.p.A.	SANT'ANNA DI VINADIO	Via Commendator G. Bertone, 1 Frazione Roviera 12010 Vinadio CN	294
ACQUE MINERALI D'ITLIA S.p.A.	PRIMANULA (LILIA)	Via Provinciale, 1 23819 Primaluna (LC)	76
	SANGEMINI	Via Tiberina, 1	514
	LYNX (AUCHAN)	Via Ponteceno, 31- Loc. Massanti 43041 Masanti di Bedonia (PR)	147
FERRARELLE S.p.A.	FERRARELLE	C.da Ferrarelle 81053 Riardo CE	718
	ACQUA VITASNELLA	Via Igea, 3 25041 Darfo Boario Terme BS	106
LETE S.p.A.	LETE	Piazza Giuseppe Arnone, 1 81010 Pratella (CE)	723
ROCCHETTA S.p.A./ ACQUA E TERME DI ULIVETO S.p.A.	ULIVETO	Via Provinciale Vicarese - Loc. Noce 56010 Ulliveto Terme - Vicopisano PI	298
	ROCCHETTA NATURALE	Zona Industriale Sud Località Madona del Piano 06023 Gualdo Tadino PG	534
SPUMADOR S.p.A.	S. ANTONIO	Via alla Fonte, 13- Cardorago 22071 Frazione Caslino al Piano (CO)	38
LAURETANA S.p.A.	LAURETANA	Frazione Campiglie, 56 13895 Graglia BI	114
FONTI ALTA VALLE PO S.p.A.	EVA	Via Roma, 61 12034 Paesana CN	216
PONTEVECCHIO S.r.l.	MONTOSO (Pam)	Via Ponte Pietra, 3 10062 Luserna S. Giovanni (TO)	201
SORGENTI MONTE BIANCO S.p.A.	FONTE OFELIA	Zona Industriale Area C 84024 Contursi Terme SA	859
SANTA VITTORIA S.r.l.	N. SANTA VITTORIA	Loc. Castello 18020 Pomassio IM	244
	N. SANTA VITTORIA SPORT		244
S. BERNARDO S.p.A.	S. BERNARDO	S. BERNARDO	241
		MAX	859
		MIN	38
		AVERAGE	306,27

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