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MSc Thesis

A Comparative Life Cycle Analysis of The Modern Milkman’s Reusable Glass Milk Bottle

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modern milkman

convenience with a conscience

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Abstract

The life cycle analysis (LCA) of The Modern Milkman's reusable glass bottles is compared against the life cycles of high-density polyethylene (HDPE) bottles and beverage cartons, to decide which packaging material had a higher carbon footprint. This shorthand LCA gives an indication on the carbon impact, taking into consideration manufacture, processing, distribution, cleaning, and EoL scenarios. This research is done on the behalf of The Modern Milkman, a company delivering milk and other fast moving consumer goods to customers around the UK.

This thesis concludes that reusable glass bottles is proven to be less carbon impactful compared to HDPE bottles and beverage cartons at a present return rate of 81%. Manufacturing is the most impactful stage of the supply chain for all packaging materials. Cleaning and distribution is an added impact for reusable glass bottles. Regarding the end-of-life scenarios of packaging, recycling of single-use alternatives is possible, yet implications with the UK recycling infrastructure is a barrier. In truth, it is ambiguous if the UKs waste is being managed properly, with much of it being sent abroad.

A breakeven point is calculated, which defines the number of times the reusable glass bottle should be used to have comparable environmental impacts as the single-use alternative. Here, the reusable bottle has to be reused 1.7 times compared to 1L HDPE bottles, and 2.0 times compared to 1L beverage cartons. When the return rate of the glass bottles increases, the number of use cycles increases, causing the production emissions to be spread over a longer lifecycle of the bottle. When the volume of single-use bottles increases, the total carbon footprint decreases and when the recycled content of the HDPE and glass bottles increases, the carbon footprint decreases.

1. Introduction

1.1 Societal Background

Food packaging plays an integral role in the safe distribution of products, designed to extend the shelf-life, and reduce food waste. Stores today stock a huge variety of packaging with a great diversity of shapes, sizes, and labels to compete between different brands. This increased choice and convenience due to supermarket culture has caused the considerable growth in production and consumption of products, and therefore packaging. The UK consumes around 5 million tonnes of plastics every year, with nearly half used for packaging (Smith, 2022). The common factor between packaging is that almost all of it is designed to be single use (Coelho et al., 2020b).

There are significant environmental burdens associated with the intense production of single-use packaging, including pollution due to waste generation and pressure on our natural resources. For example, plastic bottles have an approximate lifetime of 450 years, so if not recycled they end up in landfill, incinerated or polluting waterways and oceans (Abukasim et al., 2020). Massive increase in the use of materials that are discarded into the environment is leading to growing environmental impacts as large amounts of energy, greenhouse gases (GHG), solid and water waste and other emissions to air and water are caused by this intense production and consumption of materials (Worrell, 2016).

In 2020, the UK produced 15.8 billion litres of milk (Uberoi, 2020). In 1975, 94% of UK milk was delivered to the doorstep in glass bottles, but by 2016, the increase in supermarket culture caused a collapse in demand for doorstop deliveries, dropping to only 3% (Greenpeace, 2020). This shift was again due to the inexorable rise in supermarket culture, where the shelf-life of milk increased, and milk became much more accessible to buy. This also caused the reduction of milk prices to such a competitive price, albeit at the loss of the farmer (Butlet & Brignall, 2015). Today, around 90% of milk bottles are packaged in high-density polyethylene (HDPE) bottles (Greenwood et al., 2020). The remaining 10% of bottles are packaged in glass bottles or beverage cartons. The popular supermarket chain, Morrisons, claim that plastic milk bottles account for 10% of their total plastic sold (Doherty, 2022).

1.1.1 Developments Towards Sustainable Packaging

Food wastage due to spoilage causes more environmental damage than the packaging itself, provided the packaging is disposed of properly. Therefore, a packaging dilemma arises where “you cannot continue using current packaging methods, but you cannot abandon them either” (Knaap et al., 2020). However, we must stop the massive extraction of raw materials and discarding waste after non-circular processes with the goal to bring our production and consumption limits back in agreement with our planetary boundaries. Knaap et al. (2020) recognise recycling as the easiest yet less impactful option to change linear supply chains towards a more circular, efficient, and less contaminating packaging systems. The authors identifies the need for societal innovation towards intrinsic sustainability, seen as the long-term definitive solution for packaging. As well as circular material loops, it highlights societies finite nature and questions the polluting nature of current systems.

Advancements towards intrinsic sustainability for packaging include sophisticated sorting technologies, chemical recycling, bio-based packaging, rethinking labelling, and innovations in reusable packaging, especially glass (Knaap et al., 2020).

1.1.2 The Modern Milkman

The Modern Milkman (TMM), a start-up company that initiated this thesis was founded in 2018, triggered by the shocking volume of plastic and its effect on aquatic ecosystems shown in BBC's Blue Planet. It started as a local milk delivery of one truck in Colne, Lancashire and has quickly grown into a national network. They market their business as an option for customers to decrease their plastic footprint, support local farmers and reduce food waste by shopping little and often. Their website states that over 46 million plastic bottles have been saved since its start in 2018. This was calculated using the number of pint bottles sold being the preventative of plastic bottles bought. TMM intends to reintroduce the milkman model that includes the doorstop delivery of milk and other products such as dairy alternatives and juices in glass bottles, which are then recollected, cleaned, and returned to the dairies to be refilled.

1.2 Scientific Problem

The products transported in TMMs glass bottles, including milk, milk alternatives, milkshakes, and juices, are all considered fast-moving consumer goods (FMCG) that sell quickly at a relatively low cost due to their relatively short lifetime. The typical linear supply chain of these products are shown in Figure 1, causing massive volumes of single-use waste is generated, leaving us with the severe pollution problem we have today.

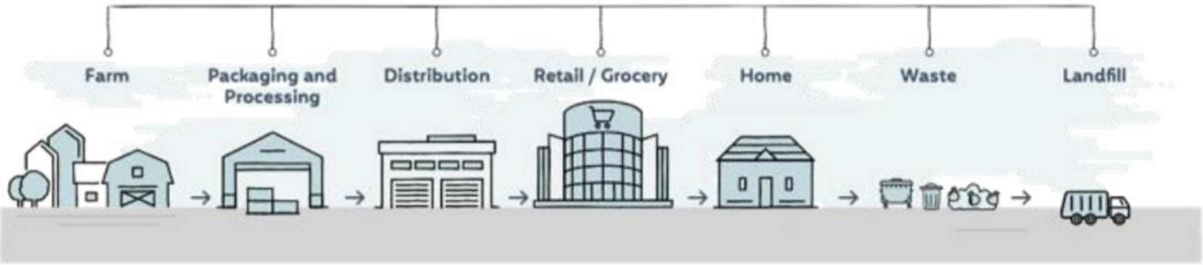

Figure 1: Linear supply chain for single-use milk bottle (The Modern Milkman, accessed March, 2022).

1.2.1 Material Selection in Packaging

Finding the most suitable packaging material is a complex task. The four main materials for packaging include paperboard, plastic, metal (usually aluminium, foils and tins) and glass, with approximately 70% used in the food industry (Galić, 2021). There is now a wide range of rigid and flexible plastics. Today, packaging usually combines several of the common materials to exploit each physical properties and function.

Marsh & Bugusu (2007) outlines the role of food packaging to contain food and protect it from damage in a cost-effect way, satisfying industry obligations and consumer needs, sustaining food hygiene, and minimizing environmental impact. Packaging plays a significant role in maintaining a products freshness and quality throughout the supply chain.

1.2.2 Milk Bottle Packaging

Despite their disadvantages, plastic HDPE bottles are durable, lightweight, and cheap to produce, meaning it is an easy choice for milk bottle packaging, although the value and appreciation is usually lost once the product is consumed. Cardboard cartons such a Tetra Pak may seem a better alternative to a full plastic bottle, yet they also follow a typical linear supply chain. Glass is a considerably heavier material than its single-use alternatives which can be seen as an obstacle in the distribution of FMCGs. Although it may seem logical to move away from single-use packaging, reasoning needs to be provided as to why the return and reuse glass bottle is the least environmentally impactful.

1.3 Research Gap

The Ellen MacArthur Foundation (EMF, 2019) state that reusable packaging is a critical part of the solution to eliminate plastic pollution. Compared to recycling a single-use bottle, reusing prevents new bottles to be made altogether, therefore reducing raw material extraction and waste generation (Mortensen et al., 2021). However, there are some case studies that find single use packaging produced lower carbon emissions. Recent literature surrounding the emissions of this increasing popular return and reuse milkman model in the UK is relatively new and produces contradicting results, discussed further in Section 2.3 and 2.4.

The varying results in literature proves the carbon footprint of packaging is extremely dependent on the defined system boundaries and chosen parameters for each stage of the life cycle. The ZWE review by Coelho et al. (2020b) analysed life-cycle assessments comparing single-use to reusable packaging. The results found the important parameters determining the success of reusable bottles to be how many times it is used, the recycled material content, the total distance it travels, and the vehicle used. The cleaning method and end-of-life scenarios also have an effect.

As glass weighs considerably more than single-use HDPE bottles or beverage cartons, the production, processing, and transport emissions may be an additional source of carbon emissions. Furthermore, the bottles need to be returned to the dairies to be cleaned, which will create further emissions. Therefore, a life cycle analysis is required to understand the carbon impact of the reusable glass bottle compared to the common single-use HDPE and paperboard beverage carton. It is also important to see where in TMM's supply chain creates the most carbon emissions, and the options they have as a business to reduce this.

1.4 Research Aim and Questions

The aim of this study is to perform a comparative Life Cycle Analysis (LCA) for the returnable glass bottle, HDPE bottles and beverage cartons. The functional unit is one unit of packaging material. The scope of the research is from cradle to grave. A cradle to grave assessment is defined as the evaluation of the impacts throughout all stages of the life cycle, from the beginning of manufacture to its end-of-life.

The research will therefore be split into one main research question followed by two sub-questions:

Research Question:

What is the CO_2 footprint of the one-pint glass bottle compared to the single-use HDPE and beverage carton alternatives?

- **SQ1:** Which steps in the glass bottle supply chain is the most carbon intensive?
- **SQ2:** What are TMM's options to reduce their carbon footprint?

1.5 Scientific and Societal Relevance

1.5.1 Scientific Relevance

The thesis is carried out on behalf of The Modern Milkman to understand the carbon footprint of their one-pint milk bottle in comparison to its single-use alternative. TMM hopes to market the hypothetical result that their reusable business model is not only preventing plastic pollution but is also less carbon intensive compared to single-use. SQ1 will identify the most impactful phases of the supply chain which can then be used to suggest various approaches TMM can use to reduce their carbon footprint (SQ2).

Recent studies have shown varying results when it comes to assessing the carbon footprint of reusable glass bottles to single-use bottles, so this case study intents to provide the scientific community of sustainable packaging with a full investigation of how and why reusable business models for glass milk bottles may or may not be successful.

1.5.2 Societal Relevance

Similar to the EUs single use plastics directive, the UK introduced a strategic ambition to “work towards all plastic packaging placed on the market being recyclable, reusable or compostable by 2025”. The UK plans of reaching a target of eliminating avoidable plastic waste by the end of 2042 (Smith, 2022). The UK’s ‘Plastic Pact’, led by WRAP and enabled by the EMF’s New Plastics Economy Initiative is a global network of businesses aiming to reduce plastic waste, stimulate new innovative business models and build a stronger recycling system. Their 2020/2021 annual report summarises that they aim to eliminate unnecessary single-use plastic through innovation, redesign, and alternative reuse delivery models (The UK Plastic Packaging Annual Report, 2021/22). TMM is a business model that can work towards this aim by reintroducing the milkman model to prevent plastic pollution.

The UK has also introduced a plastic packaging tax (PTT) this year, fining companies £200 per tonne of plastic packaging that does not meet the required 30% recycled content threshold (DEFRA, UK Statistics on Waste 2021). This study will therefore investigate the carbon footprint of a reusable bottle compared to varying percentages of recycled content HDPE bottles.

Furthermore, the British Plastics Federation (BPF) reports the UK exported 61% of its plastic packaging for recycling in 2019 because there is not enough capacity in the UK to recycle it (BPF, 2021). Turkey now receives most plastic waste (around 40%) since China imposing restrictions of plastic waste export to the UK. The problem with this intense export of the UK’s plastic waste is the little transparency of plastic management at its destination. Plastic waste, in most cases is not being managed sustainably, instead it is dumped in landfill or even worse, in the oceans. The pressure put on poorer countries to cope with the intense volume of waste the UK produces is unsustainable.

Accordingly, the contribution towards the elimination of plastic waste and its effects by preventing the need for it altogether is supported by alternative reuse delivery models such as TMM.

2. Theory

The following section will introduce the core concepts and principles followed in this research. The final chapter will provide a detailed literature review on the most recent studies comparing reusable and single-use packaging.

2.1 Circular Economy

Practically no society has been capable of decoupling economic development with material use (Strand et al., 2021). Increased globalisation and a shift in our supply chains means that it is now customary to extract raw materials in one country only to be processed and sold in another. The rising consumption of products are proving taxing on the capacity of the Earth to mitigate the impacts of the resource use and extraction.

Packaging in the UK consists of 40% of plastic consumption and over 50% paper and cardboard consumption. The advancement of simplified logistics for distributors and limited legislation on reuse has diminished the reusable packaging market and the rise of single use (Coelho et al., 2020b). The UK produced more than twelve million tonnes of packaging waste in 2020 (DEFRA UK Statistics on Waste, 2022). In 2020, the UK produced 12.6 million tonnes of packaging waste that needed to be managed (DEFRA UK Statistics on Waste, 2022). Alongside rapidly increasing waste streams, the global economy loses approximately $80-120 billion in packaging that has the capacity to be reused or recycled (EMF, 2016).

Figure 2 illustrates the environmental hierarchy of circular economy strategies, including the three innovation tracks, taken from Knaap et al. (2020). In the hierarchy of the circular economy it is clear the reuse of a product is more valuable than material recycling or recovering. In recent decades, plastic reduction strategies (such as light-weighting and other marginal improvements) were mainly in the form of decreasing material packaging per unit of packed volume (Lofthouse, 2014). However, due to increased consumer awareness around plastic pollution and the fact that recycling rates are still too low, there has been a gradual increase in focus towards reuse and the other more important strategies. In comparison to recycling, reuse prevents resource extraction and reduces energy use and waste (Mortensen et al., 2021).

The UK has pledged its commitment towards a circular economy, so for this research, in the context of a reusable glass bottle, recycling should be seen as a last resort when reuse and other CE strategies are not possible.

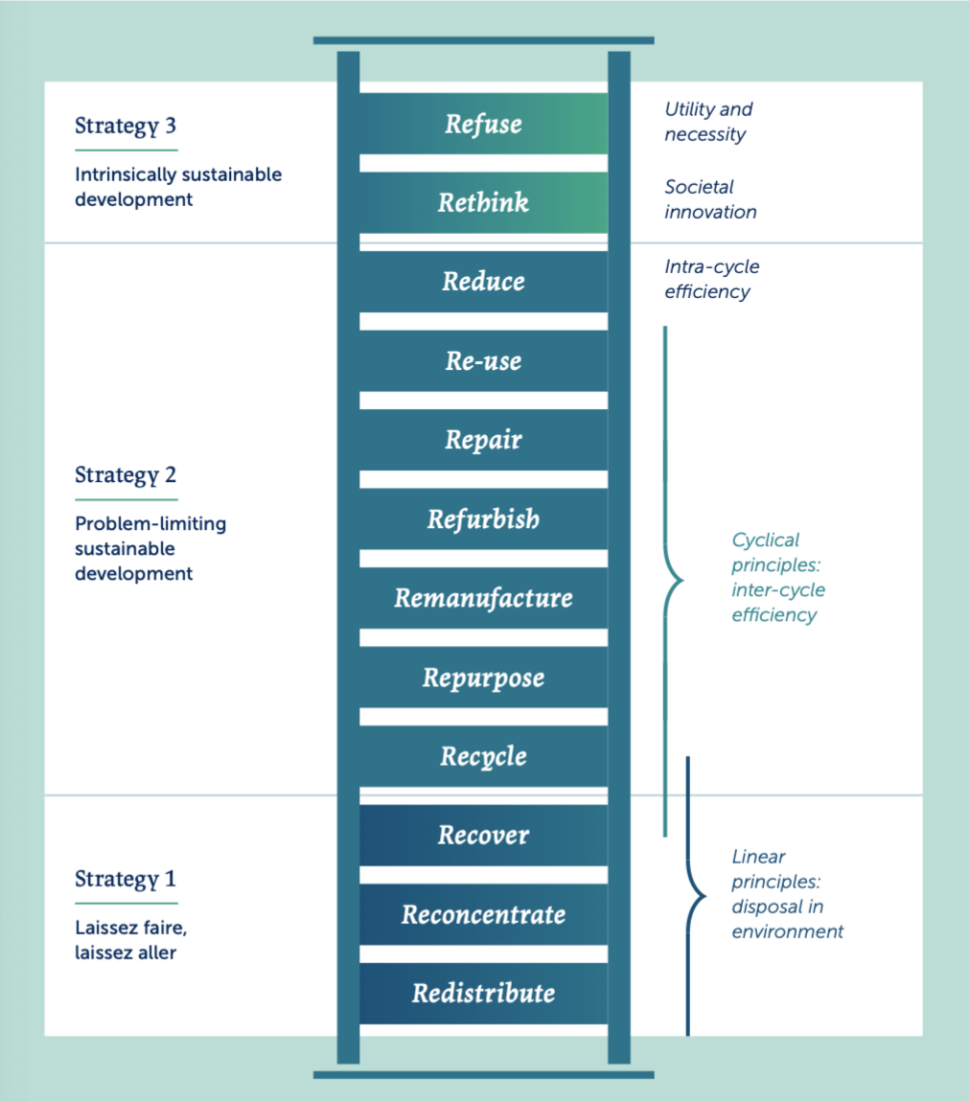

Figure 2: The environmental hierarchy of packaging strategies (Knaap et al., 2020)

2.1.1 Open and Closed Loop Recycling

The aim to prevent material losses and environmental damage is done using strategies that keep material value in the system for the longest time possible. There are recent initiatives in policies and legislation that are moving towards a circular economy to provide society with innovative technical developments and major economic investments (Bucknall, 2020). Today, the main fate for collected plastics is open-loop recycling. This involves mechanical recycling of packaging that end up re-used in different products to the one they were originally.

Alternatively, there is closed loop recycling, a preferred option for a circular economy, where the original product is recycled into the same product. Taking plastic as an example, closed-loop recycling has a limit of around 10% due to potential toxic and harmful waste residue that cannot be eliminated by mechanical recycling. Plastic bottles are a thermoset plastic, containing polymers with an irreversible bond that cannot be remelted into a new material, no matter how much heat is applied (Goodship, 2007). Once glass reaches its end-of-life phase (after around 25-30 reuse cycles (Coelho et al., (2020b)), closed loop recycling is much more possible, as it can be remelted back into another glass bottle (Dyer, 2014).

2.2 Packaging Materials for Milk

This sub-chapter describes the three most popular packaging used for milk delivery in the UK. The UK produced 15.8 billion litres of milk in 2020, with around 80% of it packaged in HDPE plastic bottles. A small percentage is packaged in cartons such as Tetra Pak and an even smaller percentage packaged in glass bottles (which was once the conventional packaging). This means that if all the milk bottles were packaged in 1L plastic bottles, there will be an annual production of over 12 billion plastic bottles just for milk.

2.2.1 High-Density Polyethylene

Food packaging materials usually comprise of polymers, metal, paper, and glass (Berk, 2018). Today, most milk is packaged in HDPE bottles, a plastic resin typically used for milk, shampoo, and detergent bottles. This thermoset plastic is a linear addition polymer produced from ethylene monomer, extracted from petroleum. Milk bottles are the single biggest use of HDPE and are produced using a process called extrusion blow moulding (Riley, 2012). It is a relatively inexpensive material, flexible and resistant to breakages. At the same time it is rigid enough to have thin walls to keep bottle weight low (Selke & Hernandez, 2001).

The key problems with HDPE milk bottles is the high production emissions per kg (due to being made from fossil fuels) and although is a relatively easy material to recycle (Singh et al. (2017), low recycling rates cause the need for landfill, incineration, and export of plastic waste. Recycling rates of all materials are given in Section 3.2.4.

Unlike glass, plastics cannot be infinitely recycled (Ogundairo et al., 2019). The performance of mechanical recycling of polymers is hindered by the deterioration of material quality. Therefore, closed loop recycling of HDPE milk bottles is limited as the technical lifespan is capped. On average, HDPE milk bottles have a maximum recycled content of 30% (Błażejewski et al., 2021). Above all, most recycled packaging does not end up being packaging again. Only 2% of global plastics are in a closed loop recycling system (EMF, 2016). Therefore, it is assumed that most HDPE bottles have a recycled content of 0%.

2.2.2 Glass

Glass is a crypto-crystalline material that solidifies at high temperatures from various domestic inorganic materials. Clear glass usually contains around 55% sand, 25% soda ash (Na_2CO_3)

and 20% limestone (CaO) (Griffin et al., 2021). On average, UK glass containers contains recyled material, known as cullet. The cullet is added the batch ingredients, giving significant energy savings. However, the main benefit results from the prevention of using raw materials by using remelted cullet instead (Griffin et al., 2021). A container glass plant typically rejects around 10% of glass, which is then recycled into domestic cullet. Then, there is the addition of foreign cullet (from external sources such as recycling plants). Green glass furnaces can have over 90% total recycled cullet, whereas clear glass is usually lower. Glass bottles are then manufactured using a process illustrated in Figure 3. The forming of the bottle is done using the press and blow process (British Glass, 2014).

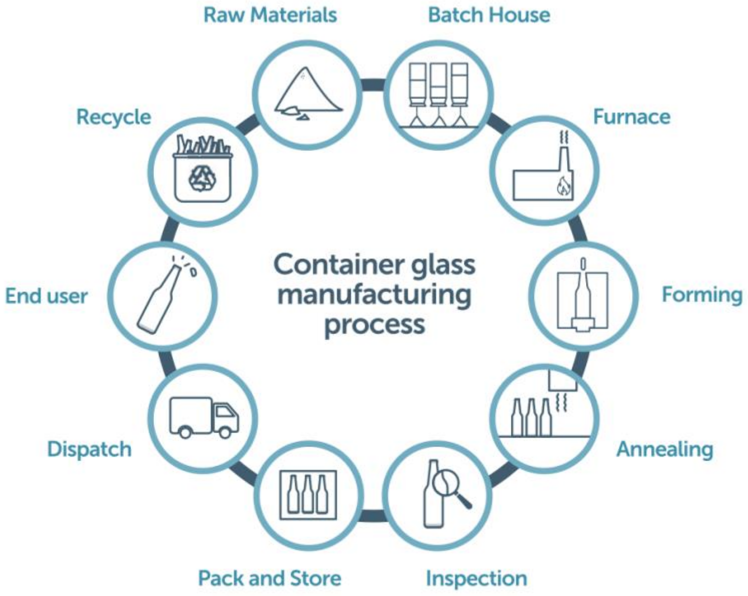

Figure 3: Container glass manufacturing process taken from British Glass (2014)

Glass bottles are 100% recyclable and can be endlessly recycled with no loss of quality or value, making it an ideal example of a closed-loop system (Modak, 2018). Glass bottles usually have a technical lifespan of 25-30 times (Coelho et al., 2020b), however different sources state that it can be more. The FAO conclude that most glass bottles make on average 30 trips (FAO, 2007). This technical lifespan can vary considerably (a crack or splinter in the bottle will send it to its EoL phase). Nonetheless, it can then be remelted and made into a new bottle, keeping the value in the system.

One of the key concerns regarding glass bottles is they are much heavier than single-use alternatives, therefore transport and production emissions may be higher. Production emissions are also expected to be high as it is an energy intensive process, however, can be reduced if the bottle reaches a certain number of reuse cycles (Griffin et al., 2021).

2.2.3 Beverage Cartons

A beverage carton is a form of packaging made predominantly from fibreboard (~75%), laminated with layers of PET plastic (21%) and aluminium (4%) (Lahme, 2020). The Alliance for Beverage Cartons and the Environment Limited (ACE UK) represents Tetra Pak, SIG Combibloc and Elopak, the leading manufacturers for beverage cartons in the UK market (Lehme et al., 2020). The carton is a lightweight, leakproof, easily transportable and strong material (Kirwan, 2011). Most long-life milk is stored in beverage cartons, however leading supermarket Morrisons recently stated the switch of their own-brand milk to cartons with the aim to reduce plastic and environmental impact (Ridler, 2022).

Beverage cartons use premium fibres that are usually sourced from Nordic conifers, meaning they are longer and offer a higher engineering performance required for cartons. However, this means that closed-loop carton-to-carton recycling is not an option due to these standards ruling out the use of recycled fibres. Therefore, recycled cartons are usually downcycled into lower value cardboard packaging (Lahme et al., 2020). Additionally, many losses occur during collection and sorting due to inefficient processing at recycling plants due to the various laminated layers needing to be separated. This is a laborious process, so the carton tends to be rejected (Lahme et al., 2020). Similarly to plastics, there is extremely low recycled content for most beverage cartons and can be expected to be zero for this analysis.

It is assumed that all beverage cartons include a HDPE plastic cap like that of the plastic bottle and is assumed to have no recycled content.

2.3 Return and Reuse

As previously stated, a change from material recycling to reuse is a positive effort within circular economy, as more value is retained within the system. Reuse is becoming increasingly recognised as a major opportunity to reduce material use and environmental impact (Coelho et al., 2020a). The EMF estimates 20% of plastic packaging could be replaced by reusable systems, something that TMM has already started realising (EMF, 2019).

There are many approaches to reuse systems, including refills in zero-waste shops and returnable deposit schemes and the traditional milkman. Zero-waste shops are yet to be fully realised, with many proving unsuccessful (Coelho et al, 2020a). Many countries are successfully using deposit return schemes for beer, soda, and water bottles, such as The Netherlands and Germany. It has proved a success due to relatively short distances for transport, smart material design and high turnover rates with it being a FMCG (Coelho et al., 2020a, Deprez, 2016). These factors are also relevant for this research when exploring the viability of the milkman model.

The milkman model involves the customer returning empty bottles to be cleaned and refilled at the dairy to be sent back to the consumer. It is a Business-to-Consumer (B2C) model where the business takes back the product to be reinserted in the production line. Ensuring the success of this business model, challenges surrounding transport, complex logistics, food hygiene and cleaning methods should be thoroughly deliberated. The following section reviews recent LCA's of reusable glass bottles compared to single-use alternatives.

The EMF state that reuse models have many positive effects from a business perspective, including cost reduction, brand loyalty, improvement of user experiences, optimisation of operations and adapting to individual needs. However, Coelho et al. (2020a) do state that reusable packaging is usually more of a financial burden compared to single-use packaging.

Butler (2022) quotes that after the COVID pandemic, customers have gone back to the supermarket, yet new customers are drawn to different and more sustainable ways of purchasing products. The author states this has had an effect on the cost of glass bottles, what has more than doubling in recent years, driven by more consumers wanting to switch from plastic to glass bottles to reduce their plastic footprint and the return to normal trading after the pandemic. Milk and More, a similar business model to The Modern Milkman are facing this financial issue, urging customers to be more conscious with returning their glass bottles on their doorsteps (Butler, 2022). Milk and More state they are adjusting their systems to increase the return rate by up to 15%, to prevent the cost of virgin glass. This is alongside a 72% increase in the price of milk, while renewable energy has tripled in price. As Milk and More have a 40% electric van fleet, this is an additional concern.

2.4 Reusable vs Single-Use: Literature Review

As mentioned, the recent literature surrounding the comparison of reusable glass bottles with single use bottles and/or beverage cartons is varying. This thesis will focus on the carbon footprint results but as most of the studies reviewed involving more environmental impacts, they will also be included. This was decided because Huijbregts et al. (2006) links the cumulative energy demand and global warming potential with other impact categories.

Not all the articles are specific to milk bottles, yet they were still included as the wider beverage market provide applicable and relevant results. The majority of LCA's that assessed these packaging materials found that glass can have the highest impact, yet under certain circumstances may prove to be less impactful (Ferrara & De Foe, 2020; Amienyo et al., 2013; Coelho et al., 2020a; Stefanini et al., 2020; Franklin Associates, 2008; Simon et al., 2016 and Postein et al., 2019).

Ferrara & De Feo (2020) conducted a comparative LCA of alternative systems for wine packaging in Italy. If the transport distance was set to 500km, reusable glass was found to be the least impactful material for all impact categories compared to single-use PET and single-use glass. However, cartons and plastic bags in boxes were found to be the least environmentally impactful in all categories. However at distances shorter than 100km the impacts of the reusable glass bottle becomes comparable to the carton and bag-in-box. Regarding global warming potential (kgCO$_2$.e), the authors found that only three reuses for the glass bottle was enough to be comparable to the plastic single use. The EoL phase for the glass bottles produced the most environmental benefits as glass has a 100% recyclability efficiency and maximum quality of recycled material, therefore preventing the production of virgin bottles.

When comparing with plastic, Franklin Associates (2008) found HDPE bottles had the lowest carbon emissions compared to the glass bottle that was reused eight times. By increasing the return rate of the glass bottle from 8 to 11.9 reduced the emissions, however, the HDPE bottle still scored better. Transport of the glass bottles accounted for a significant 25% of energy use, where its plastic alternative only accounted for 5%. Stefanini et al. (2020) had similar results for pasteurised milk packaging, concluding that although returnable glass bottles scored the lowest in marine litter indicator, it was still an energy-inefficient and transport intensive system compared to recycled PET. Returnable glass bottles had a poorer environmental performance, even at a 30-use cycle.

However, the review by Coelho et al. (2020b) discuss a clear incentive to investigate reusable packaging as 72% of the 32 papers studied indicated a better environmental performance for reusable packaging compared to single use. Of the 13 papers that were specific to returnable packaging, they found 10 papers had an overall positive environmental performance. However, it depended on specific factors, for example how many times the bottle was reused.

For most reusable packaging, the emissions are divided throughout the number of trips the bottle made. Trip rate and return rate are used interchangeably throughout this research, however, do have slightly different definitions. Trip rate is defined as the number of trips the bottle makes and return rate is the percentage of packaging, in this case bottles, that are returned by the consumer. They are used interchangeably because this thesis calculates the number or trips the bottle makes which is dependent on how many bottles TMM receives back from the customer.

Amienyo et al. (2013) state that by reusing the glass bottle just once, the global warming potential is reduced by approximately 40%, however the benefit does not increase at the same rate for the second reuse, and completely stabilises after eight reuses. This is also illustrated in Figure 4, showing the effect of increasing the trip rate of the bottle on the global warming potential indicator (gCO_2 eq/L). A steep decrease in emissions can be seen for the first number of cycles (decreased by over a third within 5 reuse cycles), then gradually reaches a plateau. As the number of cycles increases, the impact from production is spread over the increased lifetime, and the impacts then become associated with the transportation and cleaning (Coelho et al., 2021).

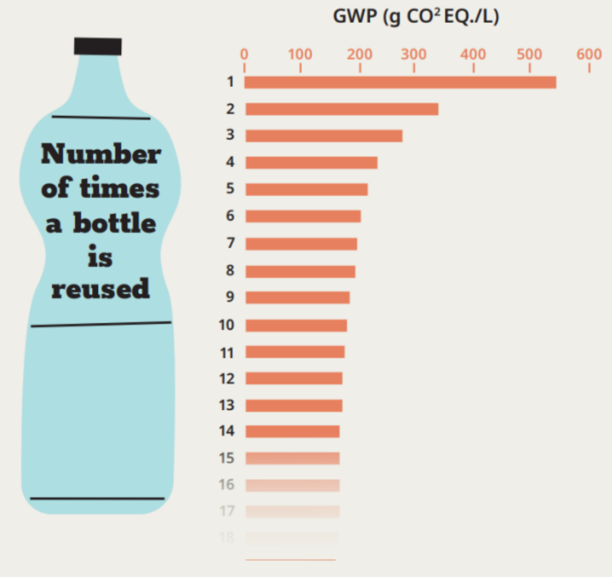

Figure 4: Number of trips and the decrease in Global Warming Potential (gCO2eq/L) taken from Coelho et al.(2020b)

As explained, the number of cycles (reuse rate) plays a vital role in the global warming potential of a bottle. There is a range discussed in literature between the minimum and maximum number of times a bottle is reused. The technical lifespan of a bottle is determined by factors such as the quality of the material and consumer behaviours. Some LCA's don't give details on the reuse (or return) rate of the bottle, which indicates doubts concerning the results. For example, Ferrara & De Feo, 2020; Simon et al., 2016 and Ponstein et al. 2019 provided no motivation for the return rate used in their results. Amienyo et al. (2013) use a total number of cycles to be 25, The review by Coelho et al. (2020) state the average reuse rate of a bottle is 25-30 times. Many other studies and references state reuse rates between 10 and 30 times.

Amienyo et al. (2013) also demonstrates the effect on the volume of packaging on global warming potential, as the reusable glass bottle was preferable compared to the 0.5L PET bottle after 3 cycles, and after 25 cycles for the 2L bottle. The smaller the volume of bottle means there is more material required per volume of packaging. Coelho et al., (2020)b discusses a break-even point (the number of cycles a reusable glass bottle has to undergo to have comparable environmental impacts compared to the single-use alternative) of usually 2-3 times. However, this is a very case specific parameter, but can be expected to be under 10 times.

The higher the percentage of recycled content of any material reduced the impact of production. This is due to the prevention of upstream processes of new material. This is supported by literature for both glass and plastic. For glass, every 10% share of cullet reduces energy consumption by 3%, CO_2 emissions by 5%, air pollution by 20% and water pollution by 50% (British Glass, 2014; Westbroek, 2021). Glass is 100% recyclable and can be made from 100% cullet, however this is unfeasible especially in clear glass containers due to colour control, defects, food contact regulations and availability/price fluctuations of cullet (British Glass, 2014). British glass states that clear container glass has a recycled cullet content of 40-50% yet other sources state recycled cullet content of around 15-30% (Griffin et al., 2021).

The most common end-of-life scenarios are recycling, incineration, and landfill, which go down in environmental favourability, when adhering to the 9Rs of circular economy. By recycling the material, especially glass with a downcycle factor of 1 (meaning no quality is lost through recycling), credits may be given as the production emissions are prevented through reuse. This can also be the case for other materials depending on their downcycle factor and the emissions associated with recycling.

To conclude, the following assumptions were derived from this literature review:

- Transport and production can be an impactful area of the supply chain for reusable glass bottles
- The smaller the volume of bottle, the more packaging material is required, increasing the production emissions
- The reuse of a glass bottle significantly reduces emissions, and levels off around 7 times
- The maximum number of trips a reusable glass bottle completes before breakage is called its technical lifespan. The average value for this found in literature is 25-30.
- The percentage of cullet in clear glass production can range from 15-50%.
- Packaging that contains recycling content has lower production emissions compared to single-use packaging
- Reusable glass has the highest EoL credit due to prevention of raw materials

Nevertheless, the key message from literature is the variance of results due to specific system boundaries and assumptions taken. Therefore it is important to gather as much accurate data as possible to have a representative study.

2.4 LCA Methodology

Life cycle analysis is a methodology to assess the environmental impact of a product of process throughout its whole life cycle. The impacts are calculated for all stages of the supply chain. It is widely used in the scientific community, governments, and private companies to model such impacts, following guidelines and standards such as ISO 14040-14044 and the ILCD (International Reference Life Cycle Data System). The communication of the impact of a product or system can shape policy and action strategies. LCAs follow an iterative process involving many feedback loops between the different phases, rather than being a pure linear process (Hauschild, 2018). An LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation, illustrated in Figure 5. Important terminology is then provided in Table 1.

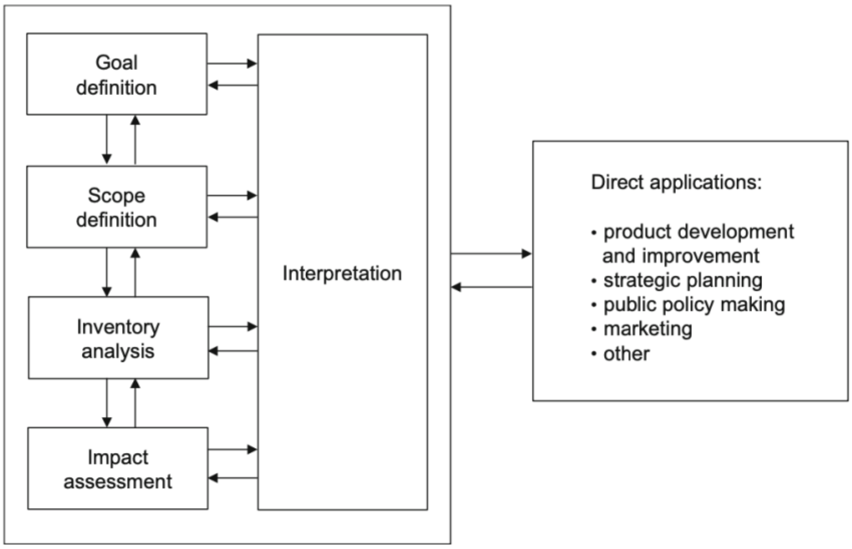

Figure 5: Framework of LCA taken from Hauschild (2018)

Table 1: LCA terminology taken from Hauschild (2018).

Terminology	Definition
Unit process	The smallest element in an LCA for which input, and output data are quantified.
Input flows	These include material and energy flows. It also includes resource flows, which unlike material and energy flows, they have been "drawn from the ecosphere with no human transformation", for example water.
Reference flow	The product flow to which all the impact and output flows are qualitatively related to the processes of the product system.
Output flows	These include products, waste to treatment and emissions.

Technosphere	Referred to as everything that is “manmade”.
Ecosphere	Referred to as “the environment” or “nature”.
Foreground system	Comprising of processes that are specific to the product system, largely modelled using primary data

Inventory analysis gathers information about the physical flows in terms of resource, material and product input and emission, waste, and product output. This is the most time-consuming phase of an LCA, and when this is complete the impact assessment translates the physical flows into communicable impacts. For the impact assessment it is necessary to select representative impact categories that align with the goal, explained further in the following section.

The **goal and scope definition** is the first phase of an LCA. According to the ISO standard, an LCA starts will a well-considered definition of the goal of the research to set the context of the study. It intends to answer why the study was performed, what research question it intends to answer and for whom the study is for. This information is given in Section 1.4 and 1.5. The analysis is then framed in accord with this goal definition in terms of functional unit and product system within geographical and temporal boundaries. The system boundaries for each three product systems (glass, plastic, and carton) are given in Section 3.1.

The second phase, **life cycle inventory analysis,** collects information regarding physical flows, inputs of materials and resources and the output of waste, emissions, and by-products. The physical flows need to be scaled in agreement with the reference flows for the determined functional unit. Allocation is dealt with in this phase: it is where each process and output is associated with its respective products and flows. The ISO suggests a hierarchy of methods when dealing such occurrences, starting with division into sub-processes, system expansion followed by physical or economic allocation. Physical partitioning is basing the value on mass or another physical quality whereas economic bases it on cost (Hauschild, 2018).

The **life cycle impact assessment** communicates the inventory analysis by presenting the data into various environmental impacts. Hauschild (2018) lists five elements of the impact assessment, of which the first three are mandatory, these include, selection of impact categories, classification of elementary flows, characterisation using environmental model, normalisation, and weighting. This research only focuses on one impact category, global warming potential, resulting from CO_2 emissions, therefore normalisation and weighting is not required.

2.4.1 Sensitivity Analysis

Once the results are presented, the interpretation phase explains the results and usually a sensitivity analysis is performed, provided in Section 4 and 5. Sensitivity analysis identifies parameters that have some variability and uncertainty, that usually affects the results. This is done to appraise the robustness of the conclusions and identify opportunities for further work. For example, for reusable milk bottles, the number of times the bottle is returned will significantly change the carbon footprint, therefore different values are modelled to understand the effect of this varying parameter. Other sensitivity parameters are highlighted throughout the next chapter.

2.4.2 Limitations of LCA

The main limitation of LCA studies is the omission of littering potential as an impact category, which is seen as a major flaw in the scientific community. Out of all the literature reviewed, only one study (Stefanini et al., 2020) considered littering potential (LP) as an impact category. They found that reusable glass bottles was had a lower littering potential compared to single-use plastic bottles.

This omission is considered a blind spot in the methodology of LCA, which can result in an underestimation of the impacts of single-use packaging compared to reusable. However this thesis aligns with the goals of TMM to introduce alternative reusable systems to replace linear supply chains of single-use packaging to reduce littering. The littering potential impact is not quantitatively measured in this thesis as only the carbon footprint is calculated, yet LP is an overarching theme to introduce reusable business models, hence is not overlooked.

3. Methods

This LCA is modelled using a tool to investigate the challenges and opportunities of reusable packaging. The purpose of the tool is to give an indication of the CO_2 impact of reusable packaging compared to single-use alternatives, in this case HDPE and other plastics. The tool was developed on behalf of the KIDV by Utrecht University and Partners for Innovation. Alongside the total carbon footprint of packaging systems, the tool can assist in calculating the break-even point for reusable packaging compared to single-use (the number of cycles the reusable packaging goes through to become comparable to single-use).

Using various primary data such as the number of cycles, processing techniques, transport distances, and means of transport, it is possible to indicate where in the supply chain is the most carbon intensive. Primary data was collected through dairy visits, hub visits and questionnaires sent via email (Appendix 1).

The tool worked with average LCA data, mainly from the EcoInvent 3.5 database and other sources, therefore for this thesis, some averages are changed to be more specific to the UK. These modifications on the tool are described throughout this chapter. Because the tool used average data, there is a limit to how accurate the calculated emissions are. Primary data inputted into the tool is also based on assumptions, so the tool can only give an estimation of the impact for each packaging system.

This chapter is split into five sections. The first defines the system boundaries, section 2 describe each of the four main phases of the supply chain: manufacture, cleaning and assembly, distribution, and end-of-life (EoL) with their accompanying assumptions. Section 3 explains the chosen allocation method, Section 4 considers important sensitivity parameters and finally, Section 5 discusses data quality requirements of the research.

3.1 System Boundaries

To compare the three packaging methods, system boundaries for each supply chain needs to be outlined, shown in Figures 6, 7 and 8. Filling, storage and consumption phases are not considered in the system boundaries due to little impact difference between the three materials. Each of the other steps of the supply chain within the system boundaries are expected to emit carbon emissions. There will be no consideration of the production milk and the food waste associated for the same reason. The production, maintenance and disposal of machinery and transport media is omitted as no significant impact is expected due to having a much larger lifetime than the functional unit.

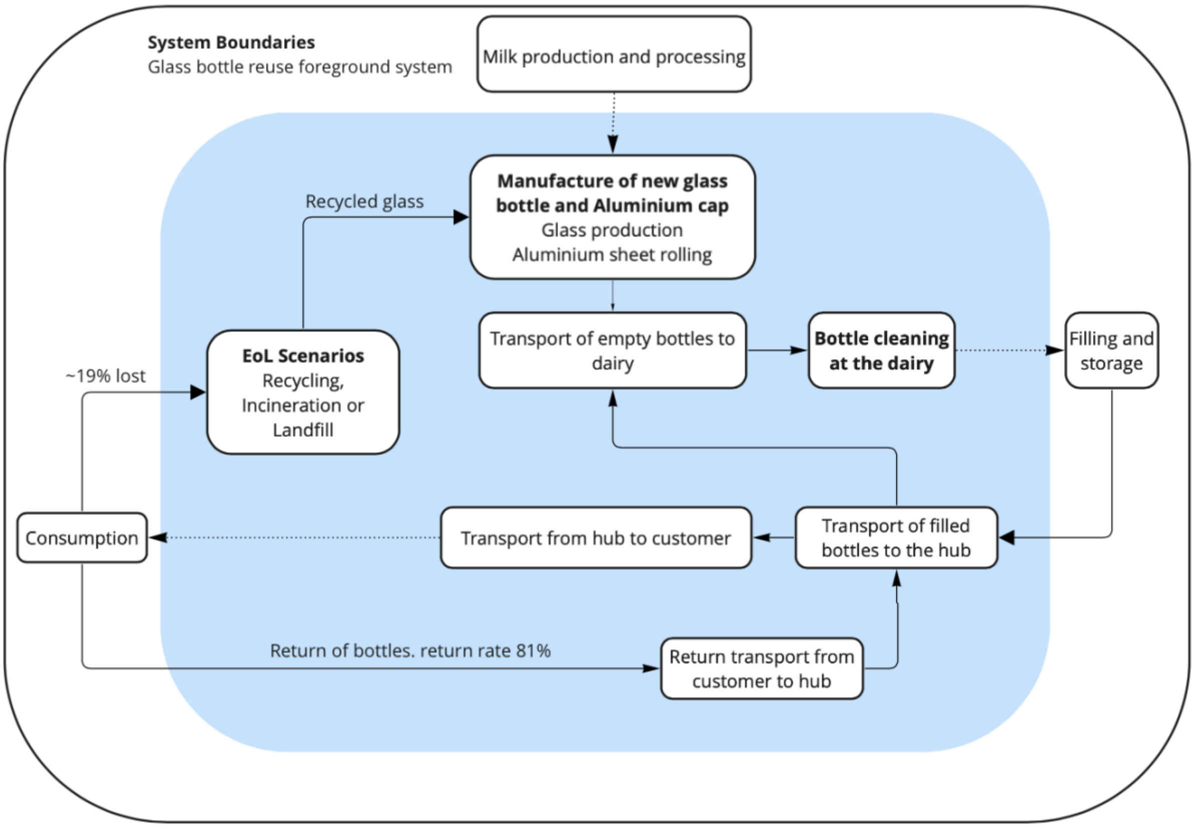

Figure 6: System boundaries for reusable glass bottle

For HDPE bottles, a linear supply chain is observed. It is assumed the transportation the customer makes to the supermarket is negligible as the emissions will be allocated to other items the customer buys, as it is more likely consumers buy more products per visit. Therefore it is assumed to be negligible. It is assumed there is no closed loop recycling and even low recycled content in the bottles, hence a dashed arrow from EoL to manufacture.

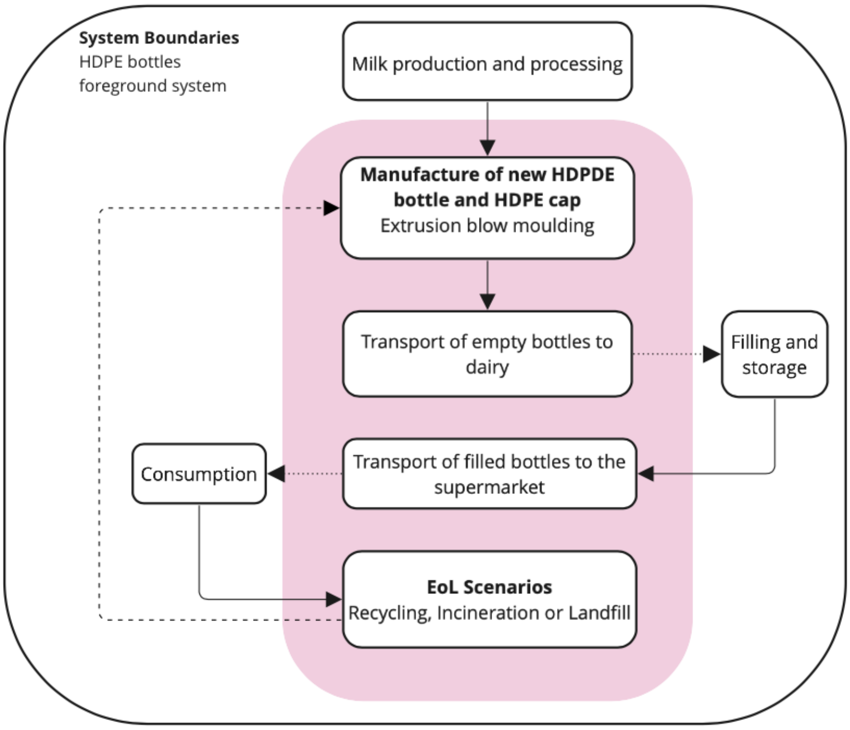

Figure 7: System boundaries of HDPE bottle

Beverage cartons follow a similar linear supply chain as HDPE plastic bottles. Here, no line is drawn from EoL to manufacturing at all because of such a low recyclability for beverage cartons, it is expected no recycled content.

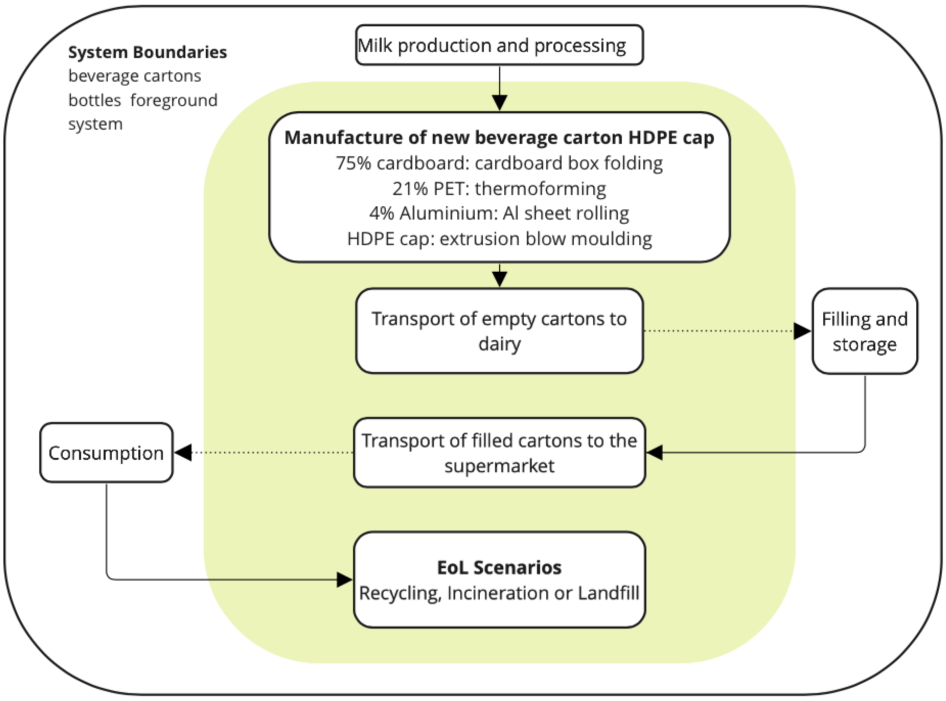

Figure 8: System boundaries for beverage cartons

3.1.1 Impact Categories

LCA’s can include any of the midpoint impact categories given in Figure 9, taken from Huijbregts et al. (2017). It illustrates that midpoint categories can contribute to damage pathways and endpoint areas of protection. The tool calculates only carbon emissions. The more impact categories included in the analysis the more comprehensive the research will be. Although it would be ideal to include as many impact categories as possible, only a quantitative carbon footprint will be done. Motivation for this is taken from Motta (2022) who states the carbon footprint “presents characteristics similar to LCA and brings less complexity in its implementation and may be a way to start implementing life cycle thinking in organisations”. Additionally the paper by Huijbregts et al. (2006) discussed fossil cumulative energy demand (CED) (and hence increased carbon emissions) as a suitable indicator for the environmental performance of products. The author confirmed a correlation between fossil CED and global warming potential, resource depletion, eutrophication, acidification, tropospheric ozone formation and ozone depletion. Therefore, for this research it can be assumed that the increase in fossil fuel use leading to increased carbon emissions, there tends to be an increase in other impact categories also.

For this reason, together with limited data and time availability for this thesis, it is favourable to limit the number of impact categories to carbon emissions to ensure a thorough and concise study.

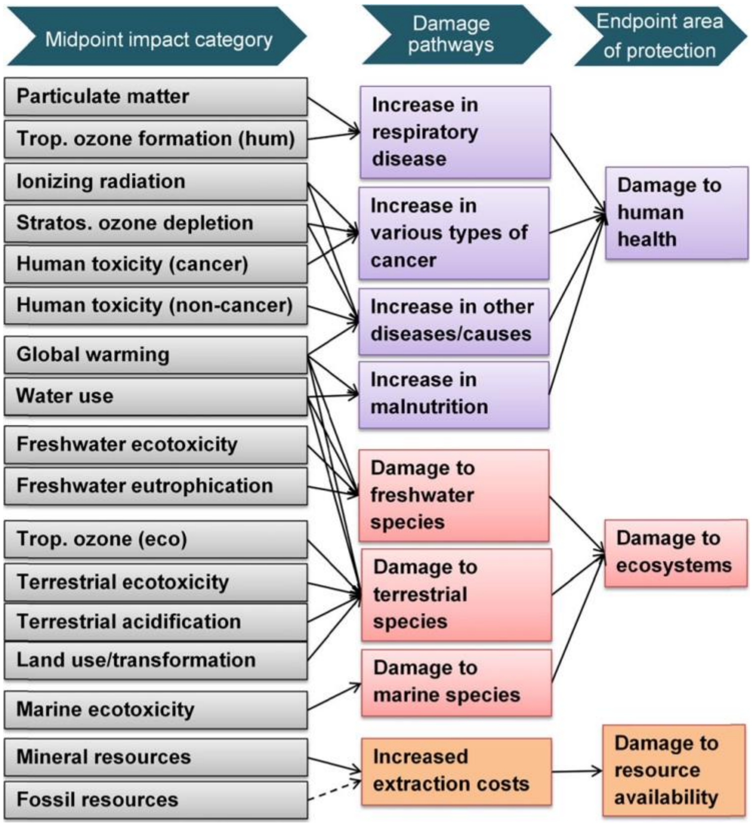

Figure 9: Midpoint impact categories, damage pathways and endpoint area of protection, taken from Huijbregts et al., 2017.

3.2 TMM Packaging Supply Chain

TMM source milk from 6 dairies in the UK: Wells Farm, Dales Dairy, Jacksons Dairy, Bates Farm, Balmers, and Threlfalls. These dairies also provide milk to companies other than TMM and can even be packaged in HDPE and beverage cartons at the same dairy. For example, Dales Dairy state they currently sell 50% of their milk in glass bottles and around 50% in plastic and the rest in beverage cartons. The dairies deliver the milk to their corresponding TMM hubs, shown in Table 2. A visual representation is provided in Figure 10 where the larger pins with black outline represent the dairies, and the smaller pins of the same colour are the Modern Milkman hubs to which they deliver. From average weekly sales data, the ratio of bottles are given on the bottom row. With Wells farm and Dales providing nearly 80% of bottles, data collection is focused on their practices. However, no communication was possible with Wells farm, therefore data provided by Dales was sometimes used as proxy.

Table 2: Dairies and their corresponding TMM hubs

Farm	**Wells Farm**	**Dales**	**Jacksons**	**Bates Dairy**	**Balmers**	**Threlfalls**
Hub	Guildford Harrow Lichfield Nottingham Sidcup Solihull Southampton Swindon Wellingborough	Leeds Newcastle Sheffield Stockton York	Jacksons SK	Warrington	Balmers	Preston
Sales	46.8%	32.2%	10.3%	6.1%	2.8%	2.9%

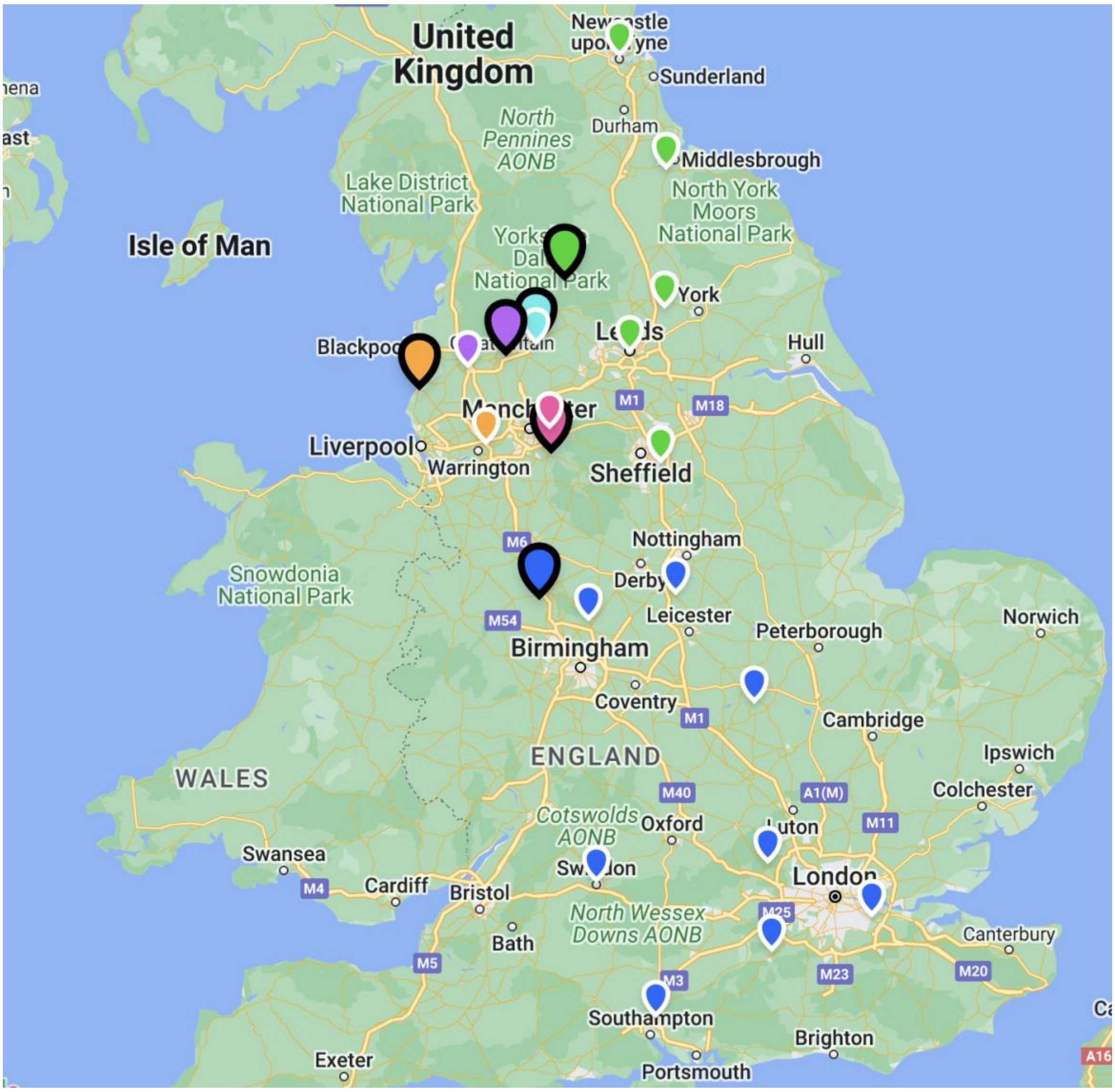

Figure 10: Map of the dairies and TMM hubs

3.2.1 Functional Unit

The functional unit is one unit (bottle or carton) of packaging used to delivery milk to the consumer. The cap for the bottle or carton is also included. Table 3 provides data for the functional unit for each packaging materials. The components for the glass bottle was provided by Seaways, a leading distributer of Ardagh Glass milk bottles (Appendix 2).

Table 3: Packaging characteristics

Material	**HDPE**	**Reusable Glass**	**Beverage Carton**
Volume [L]	0.5, 1 and 2	0.586	0.5, 1
Weight [g]	17, 31 and 40	238	25, 43
Recycled content	0%	30%	0%
Cap material	HDPE	Aluminium	HDPE
Cap weight [g]	2	0.25	2
Cap recycled content	0%	0%	0%

TMMs reusable glass pint bottle is analysed alongside HDPE and beverage cartons. A sensitivity analysis of the two single-use alternatives will be done to include the closest volumes compared to the reusable glass bottle (0.5L) and to include other volumes (1 and 2L for HDPE and 1L for beverage packaging) The variance in recycled content for each material will also be cause for a sensitivity analysis. It is assumed the caps have a recycled content of 0%. HDPE milk bottle caps are mostly coloured, meaning they cannot have a recycled content and aluminium foil caps for milk also are expected to be virgin material.

3.2.2 Manufacture and Processing

For the production phase only the primary components of the packaging are considered which include the bottle/carton and the cap. Table 4 provides information on the manufacturing process for materials used for the packaging options. For HDPE, it had to be assumed that the manufacturer for one of the main dairies, Blowplast Sheffield, was the same HDPE manufacturer for all dairies. Similarly Ardagh Glass, one of the UK’s main container glass manufacturers are assumed to be the manufacturer for glass bottles. Due to unavailable primary data from TMM and associated dairies, production emissions per kg was taken from databases rather directly from manufacturers.

In the tool, the production emissions for glass already include a share of cullet, unlike any of the single-use materials where it is possible to manually adapt the percentage of recycled material. This is because it is standard procedure for glass manufactures to include a share of cullet in their batch of virgin glass. The tool works from average databases from EcoInvent 3.5 where the percentage of cullet is a European average for white glass. There will be a discussion of the effects of cullet percentage on the carbon footprint.

For PET and HDPE the production emission factors were taken from UK government statistics for 2020 (DEFRA, UK Statistics on Waste 2020), for the rest of the materials, production emission factors were kept the same as the tool (taken from EcoInvent 3.5 database, 2018).

Table 4: Production emissions

Material	**Production emissions [CO_2.kg]**
PET	4.0324
HDPE	3.2698
Folding boxboard	1.5940
White glass	1.3260
Aluminium	19.5720

The components for each packaging that was inputted into the tool were:

- **Glass:** 100% white glass with an aluminium cap
- **HDPE:** 100% HDPE bottle with a HDPE cap
- **Beverage carton:** 75% folding boxboard, 21% PET, 4% aluminium with a HDPE cap

HDPE and polypropylene (PP) are the most common materials for plastic bottle caps, with HDPE being the most common for milk therefore was used in this analysis (WRAP, 2017). Table 5 shows the average processing emissions for different packaging materials given in the tool, taken from the EcoInvent 3.5 database (released August 2018). The carbon emissions for the manufacturing stage was calculated by multiplying the emission factor per kg by the mass of each component in the packaging.

Table 5: Process emissions

Process	**Process emissions [CO_2.kg]**
Injection moulding	1.426
Extrusion blow moulding	1.473
Injection blow moulding	1.948
Thermoforming	1.183
Film extrusion	0.609
Calendaring	0.457
Cardboard box folding	Included in production emissions
Deepdrawing aluminium	1.934
Sheet rolling aluminium	0.755
Glass production	Included in production emissions

The processes used for each packaging material was:

- **Glass:** glass process emissions were included in production emissions and the aluminium cap is processed by sheet rolling aluminium.
- **HDPE:** It is common for high volumes of bottles to be manufactured using a rotary extrusion blow moulding machine (Riley, 2012). The HDPE cap is assumed to be manufactured by extrusion blow moulding.
- **Beverage carton:** As the beverage carton is a multilayer system, a combination of processes are required. The boxboard process emissions are included in the production emissions, the PET layer is made in a process called thermoforming, the aluminium sheet layer is made by sheet rolling aluminium. The production and processes are assumed to be the same for both the single use packaging caps.

The return rate for the reusable glass bottles was 81%, calculated from 8 weeks of compliant sales and return data from the hubs. This is a relatively low return rate considering other return and reuse glass bottle systems reach up to 97% return rate (Furberg, 2021). At an 81% return rate, the bottle is reused an average of 5.26 times. This was calculated by assuming 19% of bottles are lost every cycle. For a reusable bottle, the production and process emissions are spread over how many times the bottle is used.

There is some discrepancy in the reuse rate stated by each dairy. Jacksons dairy state a reuse rate of 13 times. A sensitivity analysis will be done to demonstrate the emission savings if the company works towards increasing their return rate. For example, if TMM incentivises the return of the bottle and theoretically increases the return rate to 90%, the bottle will be reused 10 times. Coelho et al (2020b) state that glass bottles have an average technical lifespan of 25-30 times, however, as the companies return rate is low, this does not come into effect.

3.2.3 Cleaning

Once the consumer has consumed the product, the reusable glass bottles are transported back to the dairy to be cleaned. The cleaning process involves washing with hot water and detergent. It is assumed the assembly of the lids and the filling of the product has no significant impact when compared to single-use alternatives. From the EcoInvent 3.5 database, the CO_2 impact of the cleaning process based on average water, detergent and energy use was combined with a review data found from the tool authors (Table 6).

Table 6: Cleaning CO_2 impact

Cleaning	**CO_2.litre**	**water use [L]**	**energy use [MJ]**	**Detergent use [L]**
Inspection	0	0	0	0
Industrial washing (NaOH solution)	0.006	0.27	0.03	2.08
Industrial grade dishwashing	0.013	0.43	0.07	1.38
Consumer grade dishwashing	0.027	0.49	0.15	0.73
Handwashing	0.080	3.86	0.46	3.48

Each of the nine dairies have different cleaning facilities, each with varying water usage, efficiency, and energy consumption. An EU average for this process was kept constant in the tool, taken from EcoInvent 3.5. The cleaning process of the Dales dairy was taken as a proxy due to data restrictions. The cleaning process considered was industrial washing with 50% NaOH solution. Excluding the bottles that do not return to the dairy (19%), it is assumed all the bottles are cleaned by this process.

3.2.4 Distribution

Distribution of the bottles are split into five sections: transport from manufacturer to dairy, transport from dairy to TMM hub, distribution to customer, return transport from consumer and transportation to its EoL phase. Long distances travelled at any point in the supply chain has a direct link to increased carbon emissions. However, the transportation method used is important as some vehicles are more carbon intensive than others.

Transport from manufacturer to dairy

First, Table 7 provides carbon conversion factors for transportation methods. The first column presents the carbon emissions per load and km for each transportation method. The second column provides the well-to-tank emissions, also known as the upstream or indirect emissions associated with the production, processing and delivery of fuel to the vehicle. Therefore, the emission factors used will be the sum of these two values, given in the final column.

Table 7: Transportation conversion factors for transportation methods (Gov.2022 statistics).

Transportation	**$kgCO_2$.ton.km**	**WTT $kgCO_2$.ton.km**	**Final $kgCO_2$.ton.km**
Van (<3,5 ton)	0.665	0.1473	0.8123
Electric van	0.245	0.0639	0.3089
HGV >17 tonne rigid	0.179	0.0440	0.223
HGV articulated >33 tonne	0.079	0.01934	0.0983
Average HGV	0.129	0.03167	0.16065

No other transportation mode was found for other parts of the supply chain or for the other packaging materials, so the average emission factor of the two HGVs supplied by Dale's dairy was taken, 0.1607 $kgCO_2$.ton.km. This was found by calculating the average of emission factor for both HGV lorries. Although it may be the case that different transportation may be used for the other packaging, it is assumed that each material was transported using the same vehicle (average HGV) to not overestimate the emissions for one packaging method compared to another.

A weighted average distance was calculated using the ratio of total sales for each dairy and the distance from each manufacturer. The average distance travelled from manufacturer to the dairy was assumed to be:

- **Glass:** 131.94 km was the average distance from Ardagh Glass plant in Doncaster to the dairies. For the dairies that responded, most of them stated they sourced their new glass bottles from Ardagh glass or Seaway services (who source from this manufacturing plant).
- **HDPE:** 112.6 km from Blowplast Sheffield to Dales dairy was taken as proxy as no other data was found.
- **Beverage carton:** 261.4 km from the UK Tetra Pak plant in High Wycombe to the dairies.

Transport from dairy to TMM hub

Once the glass bottles are filled and capped at the dairy, they are then transported to the hubs. Again, a weighted average distance was assumed to be:

- **Glass:** 117.19 km for glass was calculated using monthly sales data for each hub and the distance from their corresponding dairy.

- **Single use packaging:** 117.19 km as it was assumed the distance from the dairies to the TMM hubs was the same as the distance the single-use bottle travelled from the dairy to the supermarket. This was kept the same as to not overestimate the emissions for one packaging over another.

Distribution to customer

For HDPE and beverage cartons, the distance the consumer travels to the supermarket is considered negligible for two reasons. First, over 80% of the UK travels less than one mile to their nearest supermarket, and secondly, usually many more products are bought from the supermarket on the same trip, therefore the impact for travelling is split over all products (Bedford, 2022).

The glass bottles are transported from the TMM hub to the consumer in a 12-valve, 1.6 L Fiat diesel van. Using an internal tool from the TMM it is calculated that the vehicle completes on average 160 drops a night. Table 8 provides a breakdown of the average distance travelled per route. From this data, an average route distance was 47.31 km.

The dirty bottles are picked back up by the milkman and taken back to the hub on the same route as the delivery new bottles. Therefore the return distance of dirty bottles back to the hub is included in the total route distance. It is assumed that there is negligible distance added onto the route for the collection of empty bottles from non-returning customers. As single-use bottles are thrown away at the consumer there is no return distribution.

A sensitivity analysis was run to account for minimum and maximum distance routes. As TMM is a fast-growing nationwide business, with many new customers every night, they intend to optimise their routes but having more customers in a smaller radius, and therefore a shorter distance travelled per night. The sensitivity analysis will also account for longer distance routes in rural areas.

Table 8: Average route distance per hub

Hub	Average route distance [km]
Guildford	46.63
Harrow	42.36
Lichfield	46.27
Nottingham	44.92
Sidcup	27.85
Southampton	33.14
Swindon	54.30
Wellingborough	37.25
Leeds	50.57
Newcastle	53.27
Sheffield	44.74
Stockton	30.43
York	37.4
Jackson's SK	54.29
Warrington	64.83
Balmers	38.1
Preston	50.73

Sensitivity analysis will also be done to account for the trialling of electric vans for the milkman's route from the hub to the consumer. The carbon impact is expected to decrease as a diesel van has an emission factor of 0.8123 kgCO_2.ton.km compared to an electric van of 0.3089 kgCO2.ton.km.

Return transportation

As the return transport back to the hubs is already allocated in the previous section, the only return transportation involves the return transport of the bottles from the hub to the dairy, where they are cleaned to be reused. It is assumed the empty bottles travel the same distance back to the dairy from the hub in the same vehicle, 117.19 km and either a 26-ton rigid HGV or a 44-ton articulated vehicle (calculated in the tool as an average HGV).

Transportation to EoL

Due to the relatively low return rate for glass bottles and the other materials being single use, it is assumed that all packaging materials are transported to EoL sorting at the consumer. The distances for each customer to recycling, landfill or incineration sites can also vary. Therefore, the average distances of waste disposal per material is taken from literature. The average distance from households to incineration was taken from the study by Bala et al. (2021), where distances for collection trucked was based on five European case studies. An average transportation of municipal solid waste to incineration plants was found to be 10 km. The same is to be assumed for landfill sites. The EEA (2020) state that current databases account 10-30 km for all inert and non-hazardous waste. They also estimate that in Europe recycling plants are further away than other end-of-life scenarios, therefore the distance is assumed to be the maximum distance of 30 km. This is done to not underestimate the impact of recycling distances, especially when the UK sends much of their recycling waste to other countries.

To calculate average distances for each packaging material, an average UK waste scenario needs to be established. For example, if 73.6% of glass is recycled with the rest being landfilled, the calculation of average distance to EoL is:

$$Average\ distance = (30\ km\ .0.736) + (10\ km\ .0.264) = 24.72\ km \qquad \text{Eq 1}$$

Using these estimated distances and packaging scenarios (explained further in the following sub-chapter), average EoL transportation distances for HDPE is 18.84 km and for beverage cartons it is assumed to be 10 km. This is because as mentioned in chapter 2.2.3, beverage cartons in the UK are not suitably recycled and are assumed to be either landfilled or incinerated.

Most refuse disposal vehicles (RDVs) in the UK are between 18 and 26 metric tons. The carbon average conversion factor for the average-weight RGV was calculated using the ratio of each weight class of RGVs (Carlier, 2022) and their corresponding conversion factors (DEFRA, UK Statistics for Waste, 2020), shown in Table 9. Therefore, the weighted average emission factor for an RDV is 0.28009 $kgCO_2$.ton.km.

Table 9: Conversion factors for UK average RDV

Weight (metric tons) rigid diesel RDV	**Vehicles in thousands**	**$kgCO_2$.ton.km**	**WTT $kgCO_2$.ton.km**	**Final $kgCO_2$.ton.km**
>7.5	1 (5.6%)	0.48056	0.11809	0.59865
7.5-18	3.2 (18.2%)	0.33572	0.08238	0.4181
>18	13.4 (76.1%)	0.18	0.04401	0.22401

3.2.5 End-of-Life

Factors determining the EoL of the glass bottle include breakage (at each stage of the supply chain) and unsuitability due to scratches and cracks. At the hub, broken bottles are put in a separated collection of glass and sent to recycling. The dairy also confirmed that the broken bottles are collected by the council as mixed recycled, Bottle losses can occur at different areas of the supply chain which will determine its EoL treatment, however, due to the low return rate at the consumer it is assumed that most bottles reach the EoL phase at the customer. Therefore an average UK waste scenario can be determined from municipal waste statistics. For glass, government statistics conclude that 73.6% of glass is recycled and 26.4 landfilled (DEFRA, UK Statistics for Waste 2022).

Equation 2 is an example of the carbon emissions from the average UK waste scenario for glass:

$$(0.7360 * Recylcing\ CO_2.kg) + (0.264 * LandfillCO_2.kg) \qquad \text{Eq 2}$$

The following EoL scenarios for each packaging option was assumed to be an average EoL scenario. For HDPE it is assumed 44.2% recycled, 17% landfilled and 38% incinerated. For beverage cartons it is assumed that they are not recycled due to its low recyclability. There was very little literature on whether beverage cartons are either landfilled or incinerated so the average carbon emissions were calculated expecting a split 50:50 incineration/landfill scenario.

To calculate the total emissions associated to the EoL scenarios of each packaging material was embedded in the tool using the Circular Footprint Formula for materials (Manfredi et al, 2012):

$$E_v + \left(AE_{recycled} + (1-A)E_v\left(\frac{Q_{Sin}}{Qp}\right)\right) + (1-A)\left(E_{recyclingEoL} - E_v^*\left(\frac{Q_{Sin}}{Qp}\right)\right) \qquad \text{Eq 3}$$

Where:

E_v = production emissions.
$E_{recycled}$ = emissions from recycled material input.

$E_{recyclingEoL}$ = emissions from the recycling process from which the credit from avoided virgin materials are deducted.

E_d = emissions from the energy recovery process of the material.

A = allocation factor of burdens and credits between recycled and virgin materials between the two life cycles. An allocation factor of 1 reflects a 100:0 approach where credits are given to the recycled content and an A factor of 0 reflects a 0:100 approach where credits are given to the recyclable materials at EoL. Here, the A factors can have three values, to be able to give credits to both aspects of recycling, which are determined by the market situation (Zampori et al., 2019):

- When A = 0.2, the equation focuses mainly on the recyclability of EoL materials
- When A = 0.5 there is equilibrium between offer and demand, so the equation focuses on both recyclability at EoL and recycled content
- When A = 0.8 there is high offer of recyclable materials and low demand, so the equation focuses on recycled content.

$Q = Q_{Sin}/Q_P$ = downcycle factor to consider the quality of ingoing and outgoing recycled materials. Q_{Sin} is the quality of ingoing secondary material and Q_P is the quality of the virgin material. For glass, the quality factor is 1 as it can be repeatedly recycled without any downgrading of quality. For plastics, this is lower as it cannot be continuously recycled as the chemical bonds in the material weakens, making the material unsuitable for packaging.

Table 10 provides emission factors for the EoL processes associated with each packaging material.

Table 10: Emission factors for EoL processes with each packaging material

Material	**$A*E_{recycled} + (1-A)*E_v*(Q_{s,in}/Q_p)$**	**Incineration CO2.kg**	**$(1-A)*(E_{recyclingEoL} - E^*_v * (Q_{s,in}/Q_p))$**	**Landfill CO2.kg**	**"Erecycled = Erecycling EoL"**
PET	2.4396	2.06	-1.18958	0.00	1.25
HDPE	1.8564	1.43	-1.08643	0.00	0.77
Folding boxboard	1.2289	0.03	-0.50392	1.041	0.73
Glass (white)	1.0615	0.00	-1.05792	0.00	0.004
Glass (green)	0.8423	0.00	-0.83872	0.00	0.004
Aluminium	15.7056	0.00	-15.46560	0.00	0.24

3.3 Data Quality

Following the ISO standard, qualities of the LCA needs to be scrutinised. Table 11 is based on the requirements set out by Meyhoff Fry et al. (2010).

Table 11: Data quality requirements (Meyhoff Fry et al, 2010)

Parameter	**Requirement**
Temporal coverage	Data should represent the situation in 2022. General data should not be more than 5 years old.
Geographical coverage	Data should represent the situation in the UK.
Technological coverage	Data should represent the current situation of the average technology mix in the UK.
Completeness	Datasets should be compared with other literature and databases to ensure all relevant input and output data is consistent.
Representativeness	The data should represent the defined temporal, geographical, and technological scope.
Consistency	The method should be applied to all elements of the analysis.
Reproducibility	The information regarding the method and specific data should allow another third party to reproduce the reported results.
Sources of data	Data should be found from credible databases and sources.

To summarise, Table 12 includes a list of the assumptions used in this research, in which a sensitivity analysis is used to model the variability of the results. Only the most significant variabilities will be included in a sensitivity analysis, as less impactful uncertainties are omitted if it does not affect the results too much.

Table 12: Summary of assumptions and consequent sensitivity parameters

Assumption	**Range for sensitivity analysis**
Return rate of the TMM's glass bottle can be increased	Currently at 81% but will test up to theoretically 95%
The introduction of electric vans in the following years can reduce TMM's impact	The full replacement of TMM's diesel fleet to a full electric fleet
There is a minimum and maximum volume for HDPE bottles and beverage cartons	0.5, 1 and 2 L for HDPE and 0.5 and 1 L for beverage carton
There is a minimum and maximum recycled content of HDPE	Up to 30% for HDPE
The various percentage of cullet	The carbon impact of the manufacturing process for glass includes a European average of cullet input. There will be a discussion on the impact of increasing the cullet based on current literature
There is variance in routes due to urban or rural environments. The introduction of route optimisation in TMM could reduce the distance travelled by the milkman, especially in rural areas.	Distances vary between minimum and maximum route distances of hubs, 27.85 and 64.83
Technical lifespan of a glass bottle has different reported values in literature	Will test for lower technical lifespan of 10 and up to a maximum of 30

4. Results

The section of this chapter will present the results found when comparing the reusable glass bottle to its single use HDPE and beverage carton alternatives. Subsequently, the results from a sensitivity analysis will show the effects of changing the return rate of the glass bottles; different volumes of single use packaging; changes towards an electric delivery fleet for glass bottles; different percentages of recycled material; and a minimum and maximum milkman route. Appendix 3 presents a breakdown of the carbon footprint at every stage of the supply chain for every outcome of the tool under these varying parameters.

4.1 Reusable Glass vs. 1L Single Use Alternative

Figure 11 presents the carbon footprint of the reusable glass bottle compared to the common 1L HDPE bottle and beverage carton. The current situation of the TMMs reusable glass bottle is at an 81% return rate and a technical lifespan of 25.

The total carbon footprint per trip was 48 grams per trip. The most carbon intensive area of the supply chain was material production/processing, which was expected from the supporting literature review. To reiterate, the processing emissions for glass was included in production emissions. The total emissions are highest for the 1L beverage carton, followed by the HDPE bottle. Reusable glass bottles had the lowest total emissions per trip. As the glass bottle is the heaviest of materials, the total distribution is more carbon intensive than the other packaging, specifically over 9 times more so than beverage cartons and over 20 times compared to HDPE bottles. Cleaning of the glass bottles add a further 6 grams of carbon per kg of packaging.

Like the conclusions from the literature review, the glass bottles had an end-of-life credit due to high recyclability of the glass bottle into new bottles, consequently reducing the overall production emissions considerably. HDPE bottles and beverage cartons had an impact for its end-of-life. Beverage cartons had considerably higher EoL impact because of their limited recyclability. Due to having a significant EoL credit, glass bottles manufacturing emissions decrease due to these credits, causing them to have the lowest impact compared to its single use alternatives.

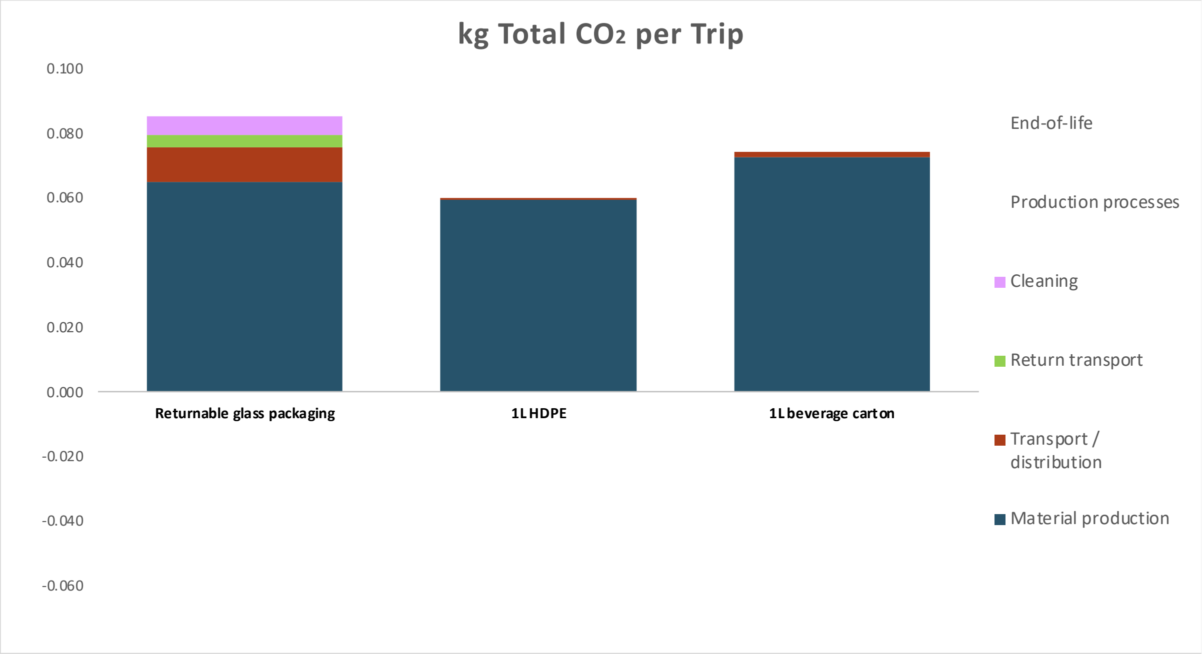

Figure 11: Carbon footprint per kg packaging material of reusable glass bottle compared to 1L single use

At an 81% return rate the glass bottle is reused approximately 5.26 times, the emissions for the glass bottle is split between the 5.26 times it is used. Hence, Figure 12 shows the break-even point, the number of times the glass bottle must be reused to have the same carbon footprint as each of its single use competitors. At first, the glass bottle has a considerably higher impact, yet reaches a break-even point at 1.7 and 2.0 times for 1L HDPE and 1L beverage cartons bottles, respectively. This aligned with the review by Coelho et al., (2020b) finding a comparable break-even point of 2-3 times. From this point, the gap between emissions continues to grow between the reusable and single use systems, as there is the need to produce a new plastic bottle or carton every time, whereas the production emissions are prevented when the packaging is reused.

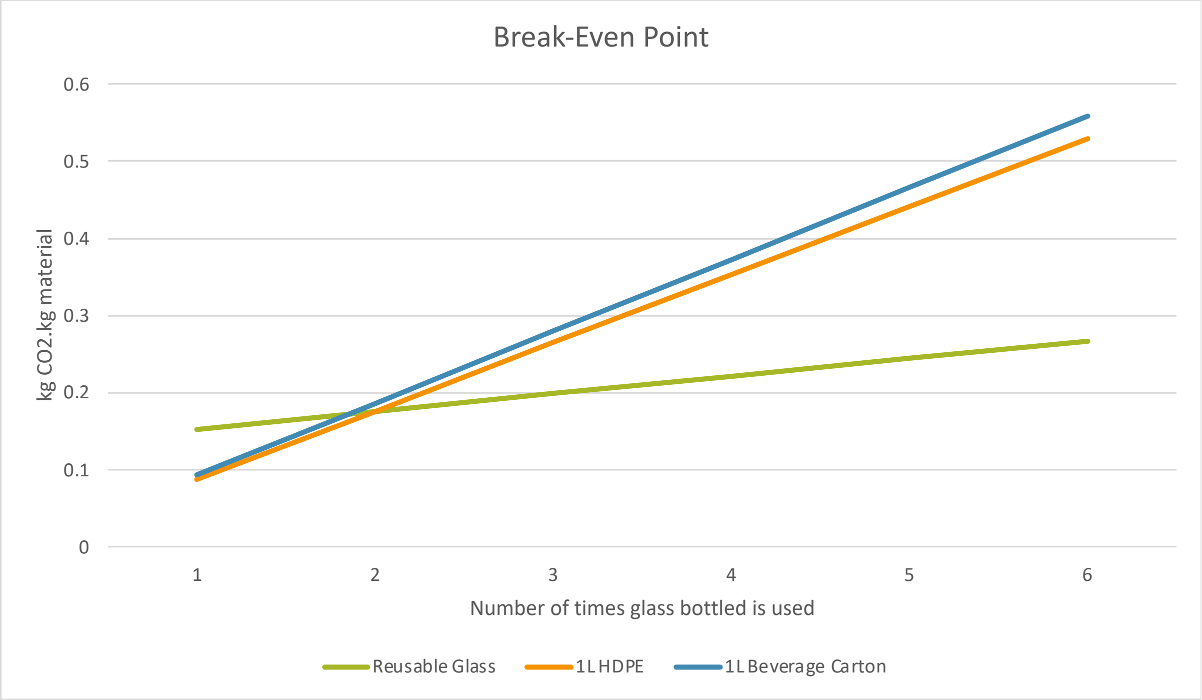

Figure 12: Break-even point for reusable glass 1L HDPE and 1L beverage carton

4.2 Increasing Return Rate

Production is the most impactful area of all supply chains. To reduce the production emissions for TMMs reusable glass bottle, the number of cycles the bottle is used for should be increased. The following results present the carbon footprint when the return rate is theoretically increased from to 90% and then again to 95%, shown in Figure 13. If the return rate is increased to 90% the bottle is used 10 times, increases to 20 times at a 95% return rate.

By increasing the return rate to 90% and 95% the total carbon emissions per trip decrease from 48 grams to 36 and 29 grams. This is due to a reduction in production emissions as the carbon impact is shared over more uses. Once the production emissions is reduced, other impactful areas in the supply chain becomes more important parameters of focus. For a 95% return rate, with the added end-of-life credit, the production emissions for glass again decreases significantly, meaning the distribution now has a comparable carbon impact to manufacture.

It may seem that the EoL credits are reduced, but this is in coordination with the production emissions as the more virgin material is produced, the more glass can be recycled and reused again, producing a higher credit. As virgin material is prevented, the EoL credit is reduced correspondingly.

If TMM was to increase their return rate to either 90 or 95%, the breakeven point related to HDPE and beverage cartons scarcely drops. The critical change by increasing the return rate is the increase in number of uses closer towards the technical lifespan. A hypothetical, yet unlikely scenario of 100% return rate would mean the technical lifespan would be achieved. Figure 14 provides another breakeven graph, but with an extended number of uses, indicating the reduction in total emissions over the total lifecycle of the glass bottle, (reaching a hypothetical technical lifespan) compared to the constant production of single-use bottles.

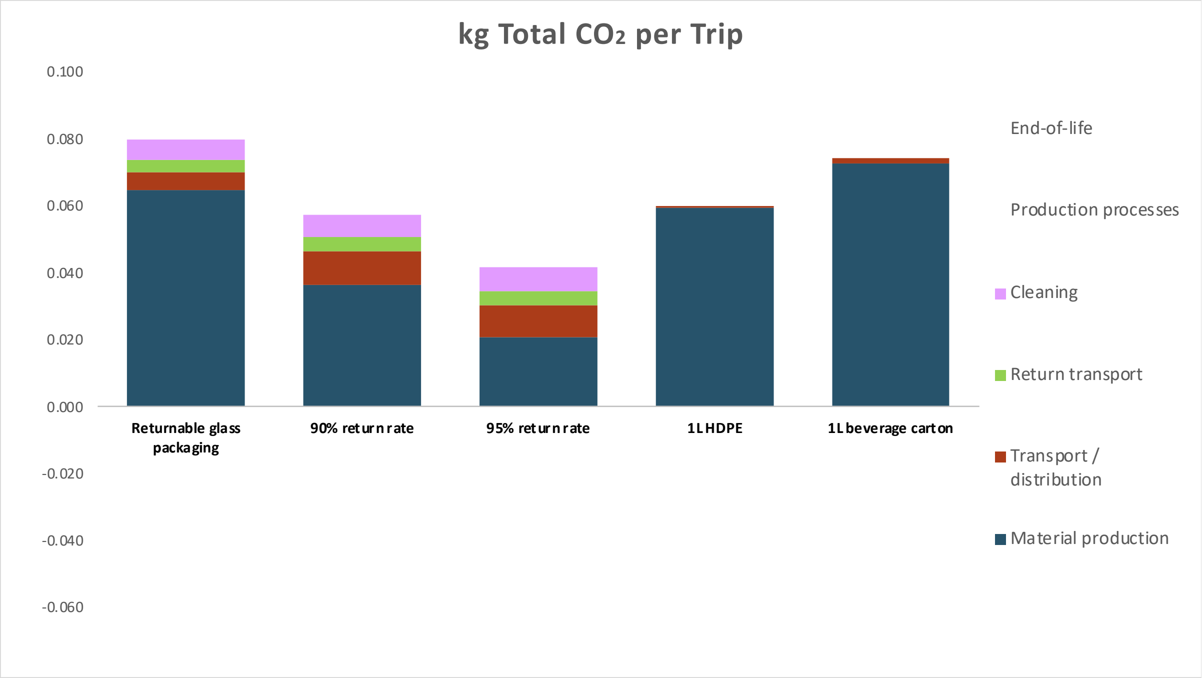

Figure 13: The carbon impact of increasing return rate of glass bottles

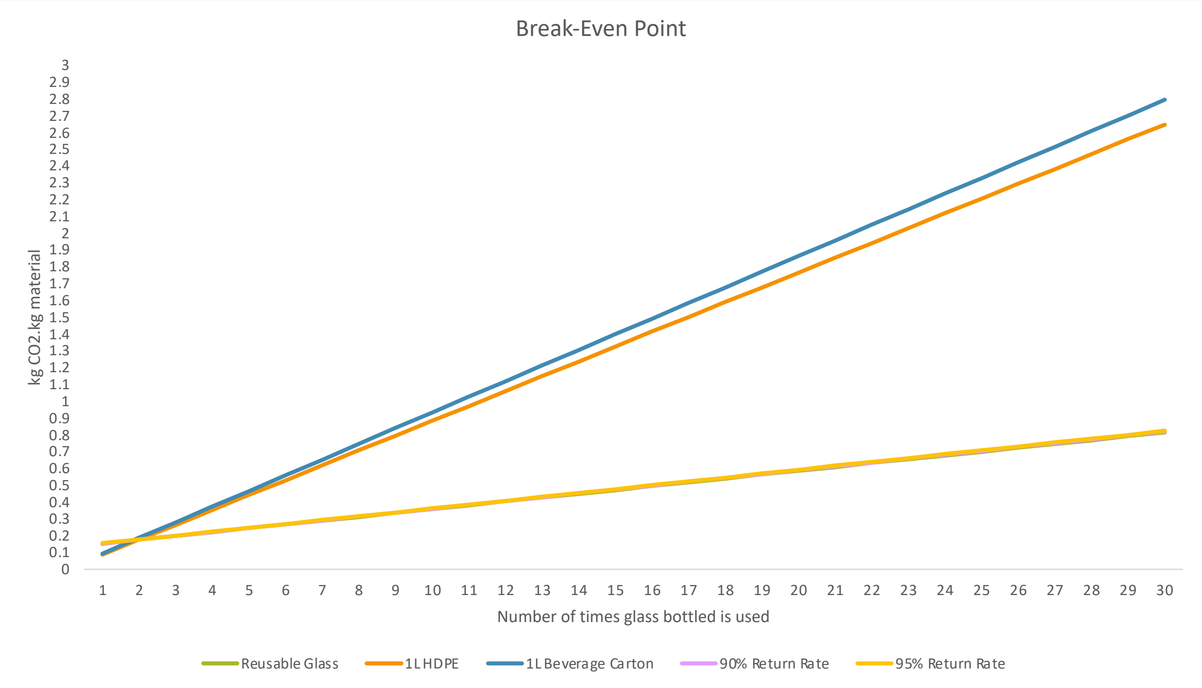

Figure 14: Breakeven point including the increased return rate

4.3 Introducing TMM Electric Vehicles

The Modern Milkman intends to introduce electric vans when delivering bottles from the hub to the consumer. Figure 15 displays the emission reduction by changing the transportation mode from the current fleet of vans (<3.5 ton) that have an average emission factor of 0.8123 $kgCO_2$.ton.km, to a full electric fleet with an emission factor of 0.3089 $kgCO_2$.ton.km.

At a current rate of 81% return rate, the introduction of electric vehicles reduces distribution (and therefore total) emissions per trip by approximately 5.7 grams for every kg of packaging materials. The same reduction in emissions was seen when introducing electric vehicles as well as a 90% and 95% return rate. Now, the reusable glass bottle only needs to be reused 1.7, instead of 1.9 times to produce the equivalent carbon emissions as HDPE, and 1.6 instead of 1.7 times for a beverage carton.

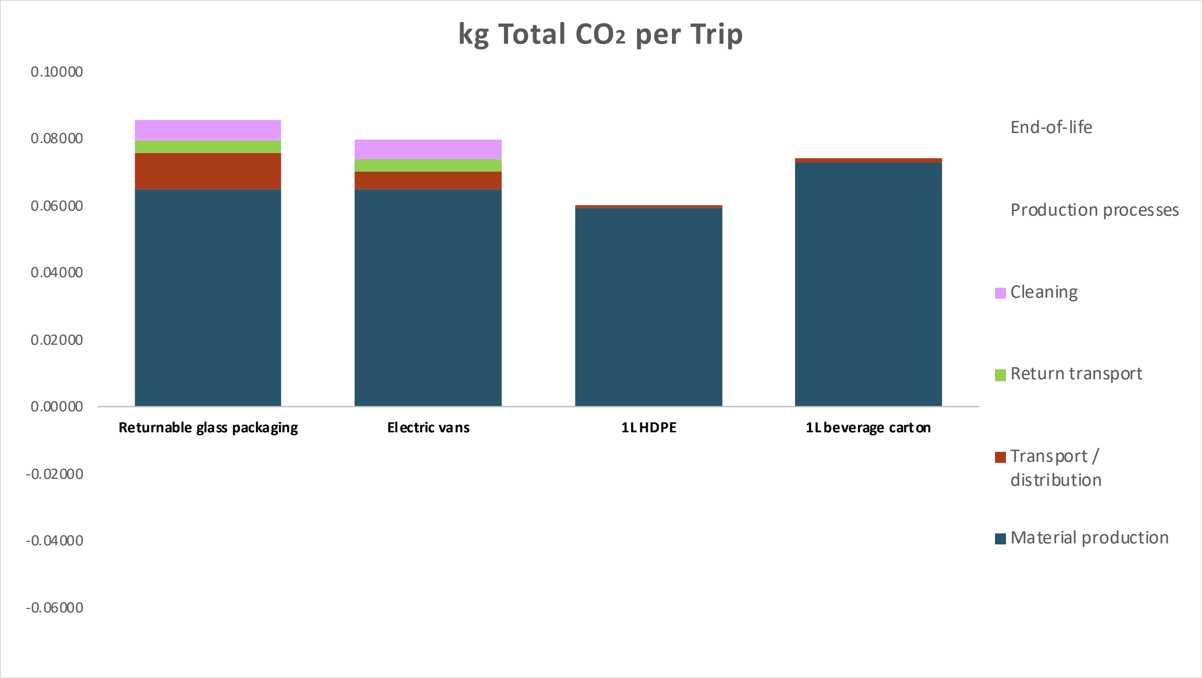

Figure 15: Carbon footprint with the introduction of electric TMM vans

4.4 Varying Percentages of Cullet

The use of cullet decreases the need for raw materials and energy needed to make virgin glass, leading to lower carbon footprints. Generally, if the percentage of cullet increases by 10%, the energy consumption is reduced by 2-3% and carbon emissions reduced by 5% (Westbroek et al., 2021) No sensitivity analysis is possible as the emissions saved due to cullet input is embedded in the manufacturing emissions in the tool. However, it can be expected that as the percentage of cullet increases, the carbon footprint of the reusable glass bottle will decrease.

4.5 Varying Percentages of rHDPE

The British Plastics Federation (BPF, 2020) aim to increase the percentage of recycled content in HDPE bottles. Currently 15% of plastic bottles contain a recycled content (rHDPE) of 30%, so a sensitivity analysis was run to model the effect of this increase. On average, a HDPE milk bottle contains 20-30% recycled content but is gradually increasing (Veolia, n.d.). This can be explained with the UK's Plastic Packaging Tax for plastic under 30%.

The production emissions for HDPE bottles decrease as the percentage of rHDPE increases, as less raw materials and fuel is required., shown in Figure 16. With 0% rHDPE the breakeven point for the glass bottle is 1.9, yet when increased to 15 and 30%, the breakeven point increases to 2.0 and 2.2 times respectively. This was a better outcome than Stefanini et al. (2020), who evaluated there was no break-even point, even after 30 uses of the glass bottle compared to single use PET bottles. The increase in global warming potential may be due to the inclusion of secondary and tertiary materials (such a pallets, crates, and labels) in this study, which was a significant contributor.

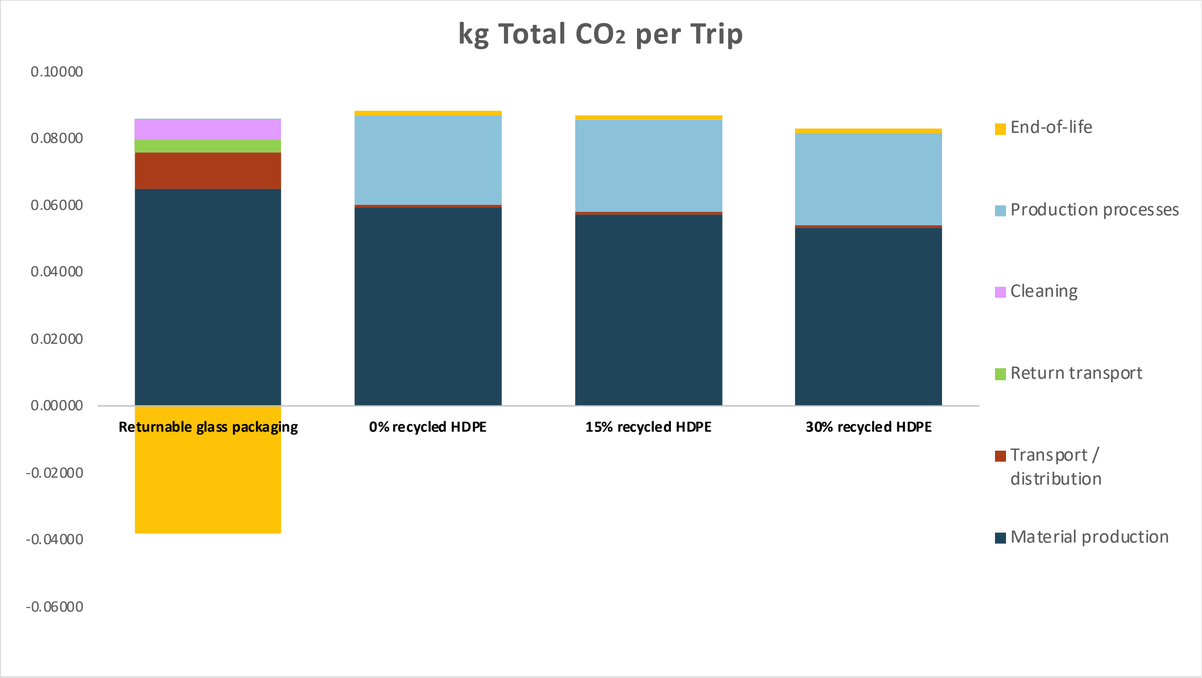

Figure 16: Effect of carbon footprint with the increase in rHDPE

4.6 Varying Volumes of HDPE Bottles and Beverage Cartons

When increasing the volume of any packaging, there is a decrease in carbon emissions as more product is being transported per mass of packaging. This is proven by Figure 17 and 18. The reusable glass bottle will need to be used 1.6 times to produce the same carbon emissions as the 0.5L HDPE bottle, 1.9 times for the 1L bottle and 3.7 times for the 2L HDPE bottle. The reusable glass bottle will need to be used 1.3 times to produce the same carbon emissions as the 0.5L beverage carton and 1.7 times for the 1L carton.

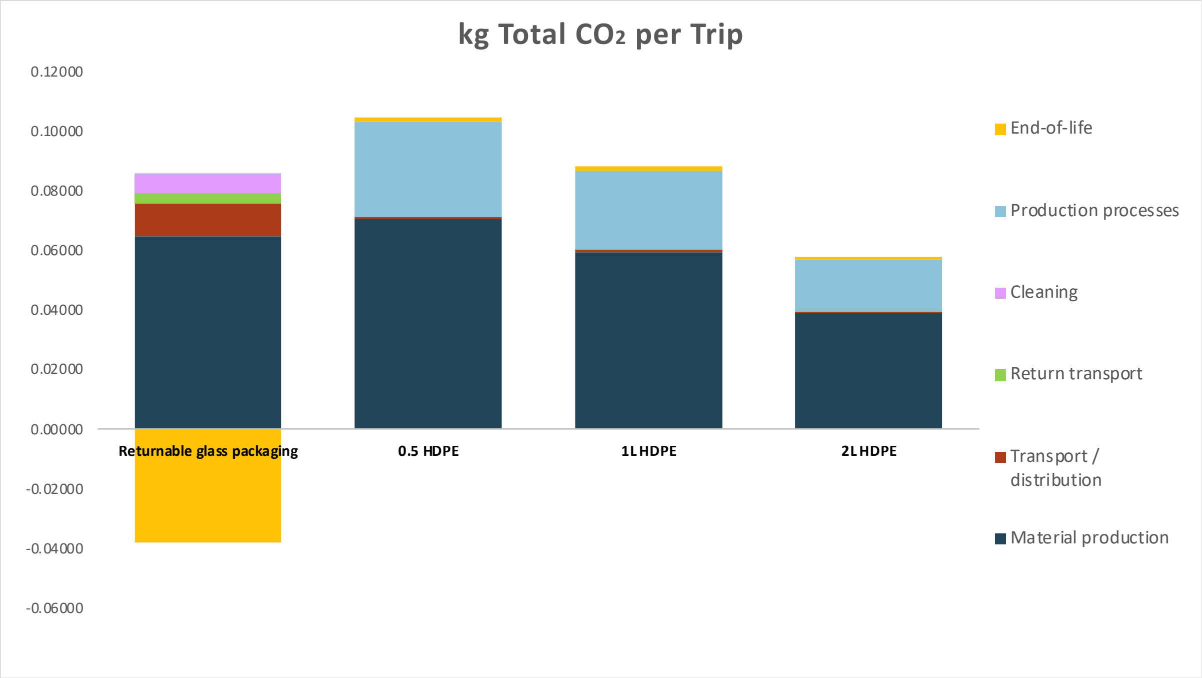

Figure 17: The effect on carbon footprint with the increase in HDPE volume

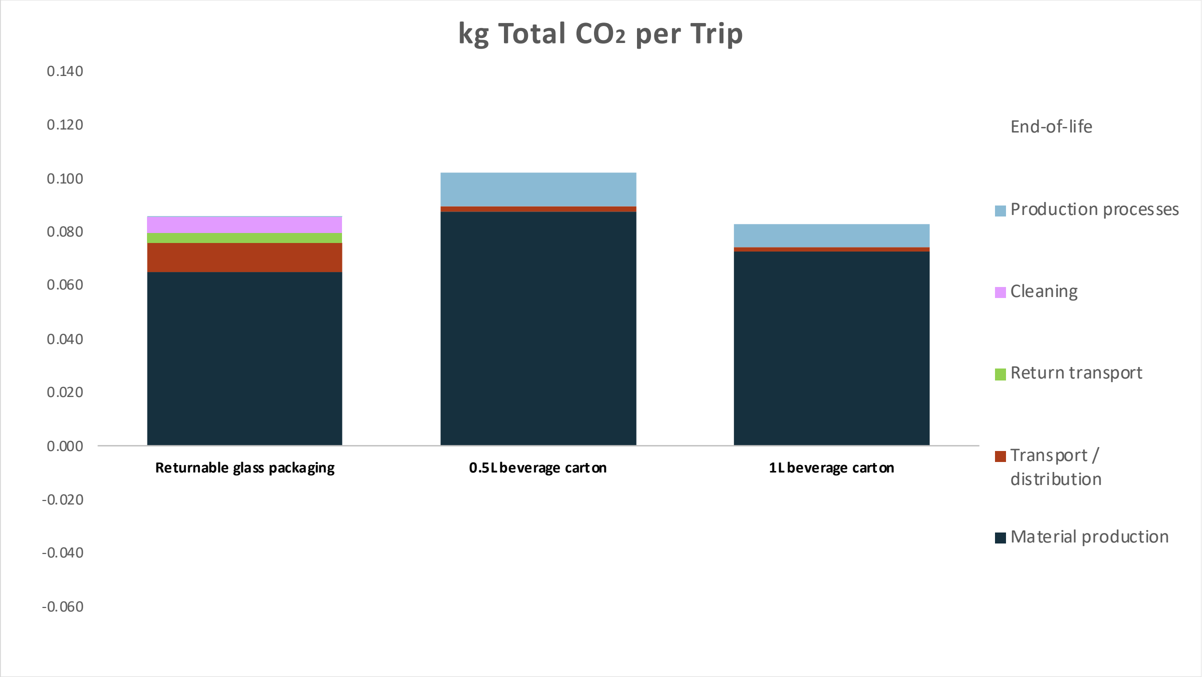

Figure 18: The effect on carbon footprint with the increase in volume of beverage carton

4.7 Varying Distances Travelled by the Milkman

A sensitivity analysis was run to model minimum and maximum distances of milkman routes, given in Figure 19. Smaller distances are expected to be in urban areas as houses are closer together, whereas longer distances are assumed to be in rural areas. The minimum and maximum distances are 27.85 and 64.83 km, respectively.

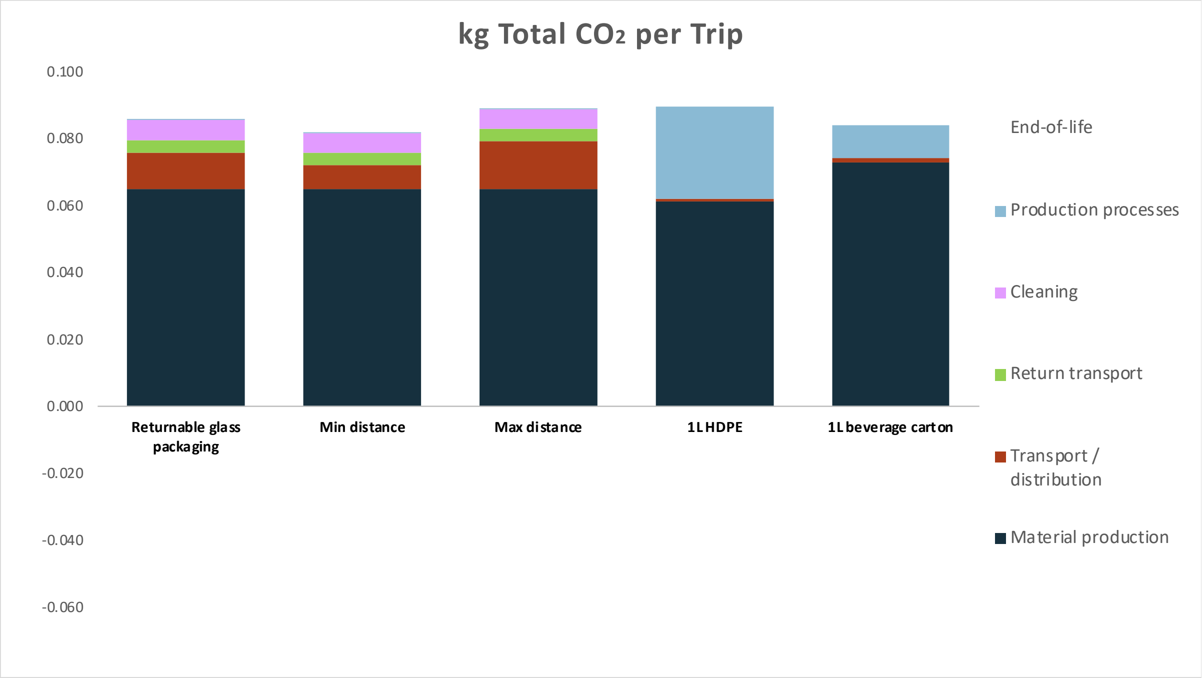

Figure 19: The effect of TMM route distance on carbon footprint

4.8 Summary of Results

The main research question and the subsequent sub-questions are repeated below:

Research Question: What is the CO_2 footprint of the one-pint glass bottle compared to the single-use HDPE and carton alternatives?

- **SQ1:** Which steps in the glass bottle supply chain is the most carbon intensive?
- **SQ2:** What are TMM's options to reduce their carbon footprint?

4.8.1 CO_2 Footprint of Reusable Glass Compared to its Single-Use Alternative

To answer the main research question, Table 13 presents the difference in total carbon emissions per trip. This thesis discovered that the carbon footprint of TMM's reusable glass bottle was less carbon impactful than its single use alternative under the system boundaries. Compared to 1L HDPE and 1L beverage carton the reusable glass bottle had 45.6 and 43.4g more CO_2 emissions per trip (at an 81% return rate there are just over 5 trips).

Table 13: Total CO_2 emissions of each packaging scenario

Packaging	**Total CO_2 emissions (kg)**
Reusable glass bottle with 81% return rate	0.0476
Reusable glass bottle with 90% return rate	0.0360
Reusable glass bottle with 95% return rate	0.0296
Reusable glass bottle with 81% return rate and electric vans	0.0419
0.5L HDPE	0.1047
1L HDPE	0.0882
2L HDPE	0.0579
0.5L beverage carton	0.1129
1L beverage carton	0.0920
1L HDPE with 15% recycled content	0.0870
1L HDPE with 30% recycled content	0.0830
Reusable glass bottle with minimum milkman route	0.0438
Reusable glass bottle with maximum milkman route	0.0510

The results show that increasing the return rate of the glass bottle reduces the impact significantly, as production emissions are spread over the number of trips.

4.8.2 The Most Impactful Stage of the Supply Chain

To answer SQ1, Appendix 1 breaks down how the emissions are spread over different areas of the supply chain (but can also be seen in the graphs), showing the production emissions is the most impactful area of the supply chain.

4.8.3 Recommendations for TMM

To answer SQ2, it is proposed to increase the return rate of the glass bottle to spread the production emissions over more trips. This can be done by introducing a deposit return scheme for the bottle, in which Coelho et al., (2020b) explain that return rates vary depending on the system, however, are positively affected by deposit fee return schemes due to the financial incentive given to consumers.

Once the return rate is increased, and the production emissions decreasing accordingly, more focus can be spent on other areas such as cleaning and distribution emissions. The launch of a full electric fleet of TMM vans can reduce the carbon impact for this area of transport, at around 5.7 grams per kg per trip. As TMM is a growing business, route optimisation is also a central option for carbon reduction.

5. Discussion

In this chapter the limitations of the research will be thoroughly explained, with detail on the importance of a sensitivity analysis to consider the uncertainties associated with this analysis. Details on how this thesis contributes to the current literature will be explained, followed by any requirements for further research. Finally, recommendations will be given, both for the scientific community and The Modern Milkman from a business perspective.

5.1 Limitations

First, it must be noted that data uncertainties were unavoidable, in which the most representative assumption was taken. The tool itself states that it does not offer a fully accurate carbon footprint, but rather an estimation of the carbon emissions. This is considered a critical limitation to the study, yet due to low data availability in TMM, it was decided to be the best practice to get a comprehensive analysis based on average LCA databases, rather than an incomplete analysis based on limited primary data.

Upstream processes such as raw materials extraction and transportation to the manufacturers are estimated through average LCA data from EcoInvent 3.5 (2018), given in the tool. These values were not changed and were kept being EU averages, so are not specific to the UK. Therefore, due to variances in processes and the UK's electricity mix, it can be expected to be fluctuate. It is unknown as to what extent it will change as it was unfeasible to know the difference in an average UK electricity mix and EU averages from EcoInvent 3.5 for varying years that was embedded in the tool.

Additionally, a main problem encountered during this research was during the life cycle inventory phase. As TMM is a start-up company, it was very difficult to find primary data, which was disorganised within many different internal programmes, rather than one main database, where it would be easier to gather what was needed. It was more of a challenge than expected to uncover exactly how the supply chain functioned. Especially during the return transport from the hubs back to the dairies, as there are issues regarding how many bottles are sent to the right dairy depending on how many they sold. Therefore it is often the case that one dairy had a surplus of bottles, and another with a deficit, causing them to buy more new bottles. Unnecessary new bottles in the supply chain increases the production emissions.

TMM are currently working towards a more transparent distribution line when returning the glass bottles to the dairies. The distance each bottle travels is inconsistent because the bottles are shared between all the six different dairies. Therefore a minimum and maximum distance the milkman travelled was included in a sensitivity analysis. The sensitivity analysis included the main uncertainties and modelled how the emissions changed for different parameter ranges. Such a growth in customers due to the business growing so much also caused logistical issues, however the sensitivity analysis did account for a minimum and maximum distance travelled by the milkman. Nevertheless it is important to highlight there is always going to be discrepancy regarding transport distance and loading factors of the vehicles throughout the whole supply chain. Depending on the day and unforeseen circumstances there may be changes in the number of stops before the dairy deliver to TMM hubs (and hence the distance travelled), the load of bottles the vehicles travel at any point of the supply chain.

Another key limitation was the omission of plastic pollution impact, quantified by the indicator littering potential (LP). However, this research expected with certainty reusable glass was less impactful in littering potential compared to single-use packaging.

Another impact parameter that was not analysed but should be mentioned is the use of water and what happens to it once it has been used to clean the bottles. It is known that Jacksons and Dales dairy do not simply dispose of their water into local waterways, it is reused as fertiliser onto the fields. This is considered a more circular approach to wastewater, over discarding it without gaining further use. Water usage and waste was omitted from the research due to data restrictions and low communication between suppliers and manufacturers. Even though there is more water required during the cleaning phase for reusable glass bottles compared to single use, that is the only area of the supply chain that it was possible to find that information. At any other point of the supply chain there was no data to see if the use of water usage was greater for glass or its single use alternatives. Therefore, from a holistic perspective this is considered a suitable opportunity for further research.

5.2 Further Work

As a resolution to the limitations of this research, a few recommendations for further work are considered. Recommendation for further work specific to TMM will be explained in section 5.4. Firstly, it is important to highlight the challenge of finding appropriate statistics surrounding an accurate representation of the UK’s end-of-life scenarios for packaging materials. For all the investigated packaging materials, there is contradiction around their EoL scenarios. For example, there is significant ambiguity surrounding recycling figures provided by the UK, as Greenpeace dispute the UK’s government recycling statistics, claiming they are much lower than stated (Greenpeace, 2021). Also, the UK statistics do not specify in what EoL category (recycling, incineration, landfill) the export of waste falls under. The British Plastics Federation state that in 2019, 61% of plastic waste was sent abroad. It is understandable to expect that UK based recycling will have lower carbon emissions compared to the export of waste to countries such as Turkey and Greece. The transport to other countries are not included in this research, so there is a motivation to further investigate how much municipal waste is exported and incorporate that in the calculations. It is also important to note that waste management in one country may be more carbon intensive than the other, dependent on processes.

Unlike other literature, the tool only calculated the impacts from the primary packaging, i.e. the bottle and the cap. Impacts from secondary and tertiary packaging such as pallets, crates, and labels are omitted from the study. To produce a more comprehensive LCA it is proposed that further exploration is done to find the additional effects of these materials.

5.3 Contribution to Literature

In terms of circular economy strategies this thesis shows that within certain system boundaries glass bottles are an excellent option for reusable B2C packaging schemes. It can be used continuously without any depletion in quality, and at EoL can be remelted back into glass bottles. This closed-loop recycling is much higher than that for plastic packaging and glass. This thesis shows that for all packaging, production is the most impactful area of the supply chain, supported by many other articles. The smaller the volume of packaging, the more production emissions increases per bottle.

Coelho et al. (2020a) express the need for further research on how consumer behaviour influences the effectiveness of reusable packaging, in which this research proves that customer behaviour is a significant factor on increased carbon emissions due to having a low return rate of return. This caused increased manufacture of new bottles and increased emissions.

5.4 Recommendations

The main recommendation for The Modern Milkman is to improve their return rates from consumers. This can be done by introducing a deposit return scheme for customers to provide more incentive to return the bottles. It is also recommended that there is better contact with each of the six dairies to allow better data communication. The questionnaire sent to the dairies only received one response. If the questionnaire was filled by all the dairies there would be more traceability and knowledge for the environmental decisions the dairies themselves make.

Coelho et al. (2020a) state that reusable packaging is usually more of a financial burden compared to single-use packaging. This can be due to return logistics and cleaning costs. As a business, TMM will attempt to keep costs as low as possible, so a cost analysis can be done to assist in decision making. Coelho et al. (2020a) also emphasise the careful investigation of hygiene and food standards for reusable packaging. This should be kept in mind for TMM however as milk deliveries have been used for many years in the UK without significant problems. In recent years, the cost of glass has more than doubled, therefore it is recommended the reuse rate is increased, not only to avoid emissions but to save costs. This can be seen as a limitation to reusable glass systems if the reuse rate is kept low.

The significant increase in renewable energy is an issue when introducing electric fleets, yet there is also an increase in fuel prices also, so a more in-depth cost analysis for electric vehicle launch would provide an interesting study.

For all packaging materials, it is anticipated that the introduction of deposit return schemes and improved recycling management can reduce packaging ending up in landfill or incineration, to be continued to be used and the value retained further into the system. Reusable systems for milk and FMCGs are growing with companies such as Loop, Our Cow Molly, and Milk and More delivery groceries to much of the UK. For business models like this to be successful, strategies such as upfront investments and effective communications should be put in place to make many more businesses like this to succeed.

6. Conclusion

This life cycle evaluation of the reusable glass bottle was compared to the lifecycle of single-use HDPE bottles and beverage cartons to decide which packaging material contributed more to global warming potential. It can be concluded that reusable glass bottles proved to be less carbon impactful compared to HDPE bottles and beverage cartons at a present return rate of 81%. Manufacturing was found to be the most impactful stage of the supply chain for all packaging materials. Cleaning and distribution was an added impact for reusable glass bottles, yet they had a credit for EoL rather than an impact associated with its single use alternatives. Recycling of single-use alternatives is possible, yet implications with the UK recycling infrastructure is a barrier. In truth, it is ambiguous if the UKs waste is being managed properly, with much of it being sent abroad. This study proved that the breakeven point for the reusable bottle was 1.7 and 2.0 times compared to 1L HDPE bottles and beverage cartons, respectively. When return rate increased, the production emissions were spread over a longer lifecycle of the bottle. When the volume of single-use bottles increased, their total carbon footprint decreased and when the recycled content of the HDPE bottle increased, the carbon footprint decreased, which can be expected for the cullet content in glass bottles. Some recent literature found that reusable glass was more carbon intensive when compared to single-use packaging, in which this thesis proved that under these certain system boundaries, was not the case.

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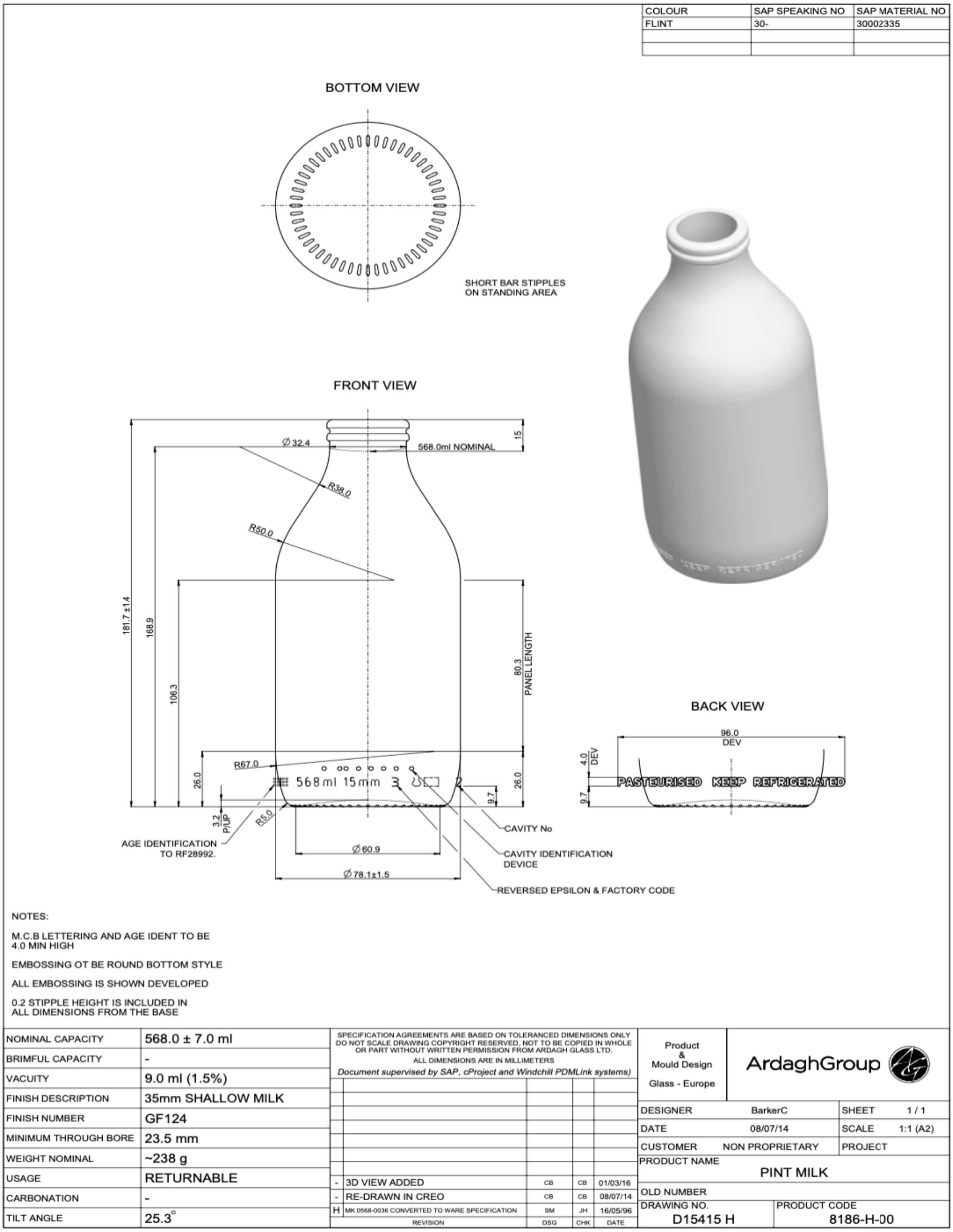
8. Appendix

8.1 Appendix 1: Glass Bottle Specification



COLOUR	SAP SPEAKING NO	SAP MATERIAL NO
FLINT	30-	30002335

NOTES:

M.C.B LETTERING AND AGE IDENT TO BE
4.0 MIN HIGH

EMBOSSING OT BE ROUND BOTTOM STYLE

ALL EMBOSSING IS SHOWN DEVELOPED

0.2 STIPPLE HEIGHT IS INCLUDED IN
ALL DIMENSIONS FROM THE BASE

NOMINAL CAPACITY	568.0 ± 7.0 ml
BRIMFUL CAPACITY	-
VACUITY	9.0 ml (1.5%)
FINISH DESCRIPTION	35mm SHALLOW MILK
FINISH NUMBER	GF124
MINIMUM THROUGH BORE	23.5 mm
WEIGHT NOMINAL	~238 g
USAGE	RETURNABLE
CARBONATION	-
TILT ANGLE	25.3°

SPECIFICATION AGREEMENTS ARE BASED ON TOLERANCED DIMENSIONS ONLY
DO NOT SCALE DRAWING COPYRIGHT RESERVED, NOT TO BE COPIED IN WHOLE
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ALL DIMENSIONS ARE IN MILLIMETERS
Document supervised by SAP, cProject and Windchill PDMLink systems)

-	3D VIEW ADDED	CB	CB	01/03/16
-	RE-DRAWN IN CREO	CB	CB	08/07/14
H	MK 0568-0036 CONVERTED TO WARE SPECIFICATION	SM	JH	16/05/96
	REVISION	DSG	CHK	DATE

Product
&
Mould Design

Glass - Europe

ArdaghGroup

DESIGNER	BarkerC	SHEET	1 / 1
DATE	08/07/14	SCALE	1:1 (A2)
CUSTOMER	NON PROPRIETARY	PROJECT	
PRODUCT NAME	PINT MILK		
OLD NUMBER			
DRAWING NO.	D15415 H	PRODUCT CODE	8186-H-00

Appendix 1: Glass Bottle Specification from Ardagh Glass

Appendix 2: Dairy Questionnaire

Dairy Questionnaire

Hello, I am working for The Modern Milkman, currently performing a Life Cycle Analysis of their reusable glass bottle. I am investigating the energy use, inputs, emissions and outputs associated with their 1 pint reusable glass bottle.

To do this I am looking for data associated with the cleaning and processing of the glass bottle through your dairy. Would you be kind enough to fill out this questionnaire in as much detail as possible, as it would be very helpful for me and TMM to calculate their environmental impact.

For inputs including cleaning materials, water and electricity, I will take the financial invoices (electricity etc.) for any time period, and then can use that with the ratio of glass bottles only, to calculate values specifically for glass bottles.

Glass and plastic ratio

1. What is the average ratio of glass bottles to plastic/cartons sales?

Transport

1. What is the standard vehicle used to transport the bottles to TMM hub?
2. What is the average percentage of TMM bottles per vehicle?
3. What is the average distance travelled to TMM hubs?
4. What are the average number of stops per vehicle before you get to TMM?
5. How many times a week do you deliver to TMM?
6. What is the average number of bottles delivered to TMM?

Assembly

1. Where do you source your aluminum caps for the bottles?

2. Guesstimating, how many times is a bottle used (I have read around 20-30 times, yet some bottles looked very old)?

3. What is the average percentage of new bottles you receive in a week?

Cleaning

1. What is the approximate amount of cleaning product(s) and lubricants you use in a week (or for any time period)?

Specific cleaning product	Amount	Manufacturer

2. What happens to the waste water and cleaning waste?

3. What happens to unsuitable bottles? Are they recycled?

4. What percentage of bottles are discarded?

Appendix 3: Full Carbon Footprint

Packaging name	**Total CO2 emissions (kg)**	**Total CO2 emissions (%)**	**Material production**	**Production processes**	**Transport / distribution**	**Return transport**	**Cleaning**	**End-of-life**
Returnable glass packaging	0.048	-	0.065	0.000	0.011	0.00363	0.006	-0.038
1L HDPE	0.090985	91%	0.0612899	0.02760991	0.00069195	-	-	0.001393
1L beverage carton	0.093164	122%	0.0727168	0.00963042	0.00155457	-	-	0.00926
90% return rate	0.03602094	-	0.0364518	0.00018875	0.010109468	0.004036888	0.0066456	-0.021412

95% return rate	0.029615	-	0.0206724	0.00018875	0.0096327	0.004261	0.007015	-0.01215
Reusable + Electric Vans	0.04188814	-	0.06485472	0.00018875	0.00529353	0.0036332	0.00598104	-0.0380631
0.5 HDPE	0.104698	120%	0.0705762	0.0317932	0.00079679	-	-	0.0015325
2L HDPE	0.057911	21%	0.0390026	0.0175699	0.00044033	-	-	0.0008982
0.5L beverage carton	0.11155284	135%	0.08761843	0.01124631	0.00186829	-	-	0.0108198
15% recycled	0.08701114	0.8294153	0.05731593	0.02760991	0.00069195	-	-	0.00139335
30% recycled	0.08303719	0.74586274	0.05334198	0.02760991	0.00069195	-	-	0.00139335
Reusable + Min distance	0.043796	-	0.0648547	0.0001887	0.00720155	0.003633	0.005981	-0.038063
Reusable + Max distance	0.050952	-	0.0648547	0.0001887	0.01435831	0.003633	0.005981	-0.038063