Life Cycle Assessment of coffee consumption: comparison of single-serve coffee and bulk coffee brewing

Final Report

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Executive summary

Context

According to the United Nations Environment Programme (UNEP) and the World Resources Institute (WRI), one third of all food produced worldwide is wasted. In an effort to address the issue, PAC launched the PAC FOOD WASTE initiative to investigate the causes of food waste, identify innovative packaging solutions, extend product shelf life and inform and educate the broader community. One of the initiative's first projects aimed to elucidate the relationships between North American packaging and the causes of food waste along the food value chain through a life cycle assessment (LCA) of coffee systems whose key differences lie in their packaging and coffee brewing process. PAC therefore commissioned Quantis to conduct a formal ISO 14 040-44-compliant LCA study comparing the environmental performances of single-serve coffee using a capsule system and bulk coffee using a drip-brewed system for one 8-oz. serving of filtered coffee in the North American market. The aim was to answer a series of questions, including:

- What is the environmental footprint of single-serve coffee and how does it compare to the footprint of drip-brewed coffee?
- How do consumer habits influence the life cycle impacts (brewing and waste, disposal of the grounds and expired bulk coffee)?
- What is the percentage of each input (including packaging) in the overall footprint, from coffee bean growing to brewing to product and packaging disposal?

Life cycle of a coffee system

The study assessed the life cycle of brewing coffee using single-serve capsules (system 1) or bulk coffee (system 2), from the extraction and processing of all raw materials to the end-of-life management of the coffee and packaging system (see figure i).

The single-serve capsule was modeled to represent a generic capsule based on current designs that uses standard abaca filter. The drip-brewed coffee system was modeled to represent a generic no. 4 standard abaca filter based on current product and packaging designs and a generic bulk coffee packaging system based on current designs.

Figure i: Summary of the life cycle of one serving of coffee and the life cycle impact assessment method IMPACT 2002+ vQ2.21

In order to provide a practical, comprehensive overview of the product system, the LCA considered all identifiable upstream inputs in each life cycle stage. For example, truck transport emissions as well as the impacts of the additional processes and inputs required to produce the fuel were considered when determining the environmental impact of transportation. The production chain of all inputs can therefore be traced to the initial extraction of raw materials. As illustrated in Figure i, the systems are divided into five main life cycle stages: (1) Coffee supply, (2) Materials and production, (3) Distribution, (4) Use, and (5) End-of-life.

The method used to evaluate the environmental impact is the peer-reviewed, internationally recognized IMPACT 2002+ vQ2.21 life cycle impact assessment (LCIA) method adapted by Quantis, which considers 17 different potential impact categories (midpoint) and then aggregates them into four damage (endpoint) categories: climate change, human health, ecosystem quality and resource depletion (see Figure i). They are presented along with the inventory indicator for water withdrawal, which is not yet accounted for in any endpoint category.

A critical review of the study was carried out by a panel of external experts that included Gregory A. Norris (Harvard T.H. Chan School of Public Health), Terrie Boguski (Harmony Environmental) and Getachew Assefa (Triple Ten Consulting) to validate compliance with ISO 14 040-44 standards. The results of the critical review are available in Appendix E.

Consumer behaviours and energy efficiency: key parameters

The coffee systems considered in this study provide very different consumer experiences, and consumer behaviours are vastly different.. Consumers have virtually no control of inputs and outputs of the single-serve system. Conversely the consumer controls all aspects to the drip-brewing process including the amount of coffee brewed, the amount of water used and the amount of time the coffee is left on the hot plate. The results presented in this report indicate that consumer behaviours pertaining to coffee waste and energy use constitute key parameters when determining the environmental performance of a coffee system. Unfortunately, there are few reliable studies or surveys on consumer behaviours in the literature. As a result, this study relied on a series of scenarios tested with sensitivity analyses to pinpoint the tipping points of system comparisons.

It was anticipated that the drip-brewed system would generate two types of coffee waste: **coffee waste due to over-preparing** (i.e. when the consumer brews more coffee than necessary to avoid shortage) and **coffee waste due to inferior freshness** (i.e. when the consumer disposes of a certain amount of bulk coffee before it is consumed in its entirety due to lack of freshness since bulk grains are kept over a longer period of time). In addition, certain drip-filter brewers are equipped with a **hot plate to keep the coffee warm** for a certain period of time—a feature that impacts the energy efficiency of the coffee making process. Certain coffee makers will have an auto shut-off feature that minimizes the time of use of the hot plate, while other models will keep the coffee warm for longer periods.

In single-serve systems, the type of capsule and coffee machine determine the amount of coffee used and brewed, virtually eliminating any risk of coffee overconsumption. In addition, the capsules contain a single serving of coffee, which remains fresh until the capsule is inserted into the brewer, thus also considerably limiting the risk of waste due to inferior freshness. For these reasons, neither type of coffee waste was included in the single-serve system scenarios. However, the energy efficiency of single-serve coffee machines varies according to the type of heater, parts insulation and available features. **Flow-type heaters are the most efficient coffee machine water heaters** since they are only activated for brewing and switch off immediately afterwards (the automatic shut-off feature is not required). Machines may also have a ready-to-serve mode, which is a preheat function requiring that the coffee machine be equipped with a reservoir of water that is kept at 85°C to 90°C at all times for immediate brewing. **In this study, coffee machines equipped with a ready-to-serve mode were considered to be the less efficient option**.

These different behaviours were taken into account when setting out the scenarios in Table i.

Table i: Study scenarios

System 1 **Single-serve coffee**	System 2 **Drip-brewed bulk coffee**
S1a Single-serve, efficient One serving of single-serve coffee using a machine with a flow-type heater: BEST CASE	**S2a Drip-brewed, accurate** One serving of drip-brewed coffee for an accurate amount of coffee and no coffee waste, heated with a hot plate for 37 minutes: BEST CASE
S1b Single-serve, ready to serve feature One serving of single-serve coffee using a machine with a ready-to-serve feature: WORST CASE	**S2b Drip-brewed, 50% coffee waste over-preparing** One serving of drip-brewed coffee with 50% waste due to over-preparing
	S2c Drip-brewed, 30% coffee waste, loss of freshness One serving of drip-brewed coffee for an accurate amount of coffeeand30% coffee waste due to inferior freshness retention
	S2d Drip-brewed, 50% coffee waste over-preparing, 30% coffee waste loss of freshness, 2 hours of heating One serving of drip-brewed coffee with 50% waste due to overconsumption and 30% coffee waste due to inferior freshness retention, heating with a hot plate for 2 hours: WORST CASE

Results and conclusions

The adoption of a single-serve coffee system by North American consumers would realize significant environmental benefits including coffee waste reduction. Additional benefits could be achieved with the development of coffee machines with better energy-saving capabilities and extended service lives.

The single-serve coffee system's packaging generates more packaging waste. However, when considering the entire life cycles of each system, the amount of coffee required making up for consumer waste and the electricity consumed for brewing (which depend on consumer habits and coffee machine features) drive the differences in impact.

Overall, the single-serve best case scenario posts a better environmental performance than the drip-brew system from the perspective of the systems' full life cycles. This advantage is specifically attributable to:

- Typical consumer behaviours, including waste due to coffee over-preparation (S2b) and inferior packaging freshness retention (S2c), which cause the drip-brew system to generate greater impacts;
- The amount of coffee required to make up for consumer waste and the electricity consumed for drip brewing, which further increase the overall footprint of the drip system;
- Minimal coffee waste by the single-serve system, which provides an exact serving of coffee even though it creates more packaging waste.

When compared, the best case scenarios for both coffee systems (S1a and S2a) are considered equivalent from the perspective of the climate change indicator (see figure ii). Furthermore, the single-serve coffee system with a ready-to-serve feature that keeps the water hot for immediate coffee preparation (S1b) generates a more significant climate change impact than the best case scenario for the drip-brewed coffee system (S2a). But the best case scenario for the drip-brewed coffee system (S2a) is not representative of average consumer behaviours since bulk coffee brewing is not always accurate and consumers tend to make more coffee than necessary to avoid shortage. The climate change scores were sensitive to consumer behaviours, and, when assessing all of the study scenarios, the coffee waste and electricity consumption parameters were found to affect the indicator results:

- Only 2% coffee waste due to over-preparing and approximately 3% coffee waste due to inferior freshness retention push the climate change score for the drip-brewed system higher than the score for the single-serve best case scenario.

- When compared to the less efficient single-serve coffee machine (ready-to-serve mode, S1b), the tipping points for coffee waste due to overconsumption and inferior freshness retention are 23% and 30%, respectively.
- When both types of coffee waste (50% due to over-preparing and 30% due to inferior freshness) are considered in the same scenario (S2d) along with the longer use of the hot plate (2 hours versus 37 minutes), the gap between the impact scores of the two studied coffee systems widens further.

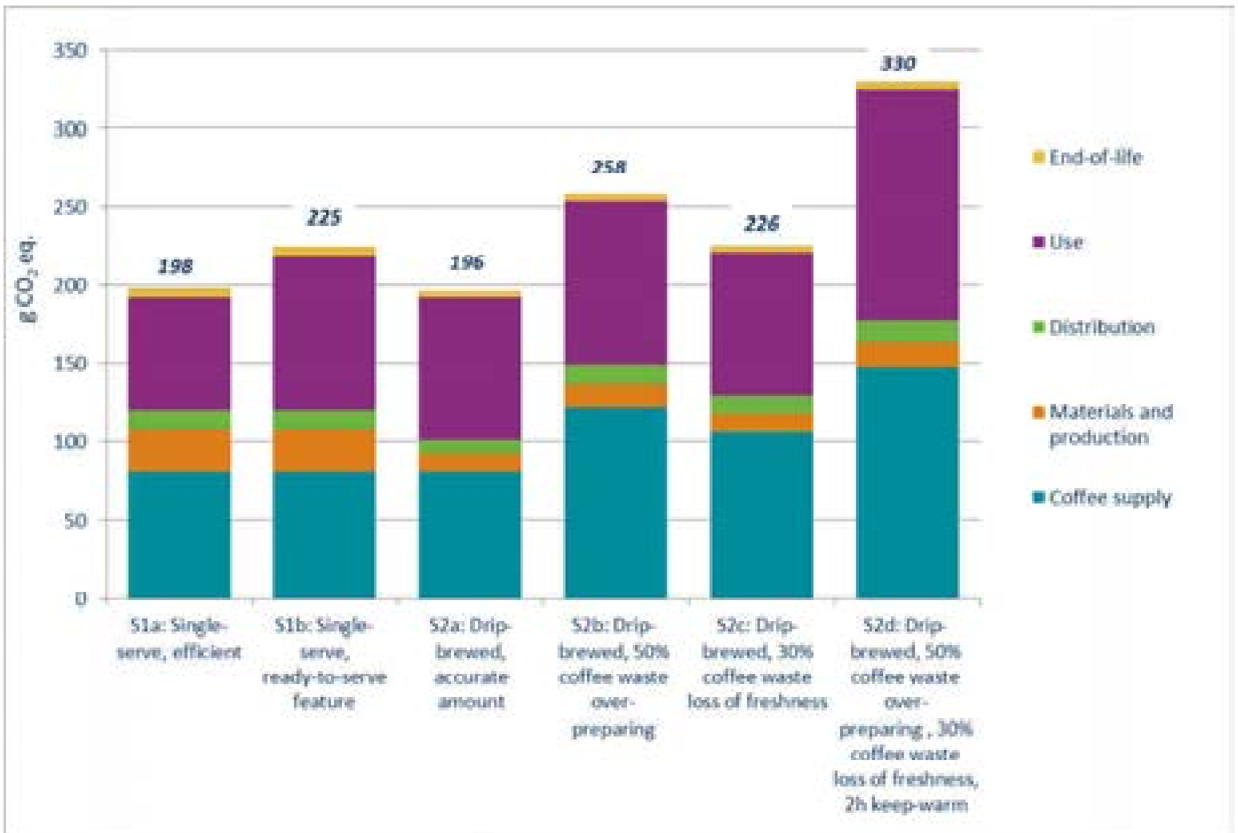

Figure ii: Comparative results for the climate change indicator

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Abbreviations and acronyms

Al	Aluminum
CO_2	Carbon dioxide
cm	Centimetre
DALY	Disability-adjusted life years
EOL	End-of-life
EVOH	Ethylene vinyl alcohol
FAO	Food and Agriculture Organization of the United Nations
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential (generally in g or kg of CO_2 eq.)
Ha	Hectares
HDPE	High-density polyethylene
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometre
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment (method)
LDPE	Low -density polyethylene
LVF	Large volume factor
m	Metre
MJ	Megajoule
PAC	Packaging Consortium
PDF	Potentially disappeared fraction
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
R&G	Roasted and ground
T	Tonne
USEPA	US Environmental Protection Agency

1 Introduction and context

Heightened concern about environmental sustainability and consumption habits has focused attention on understanding and proactively managing the potential environmental consequences of products and services. Tea and coffee capsules receive a disproportionate focus in such discussions because of their single-use property and contribution to the waste stream. In addition, the estimated penetration of single-serving brewers in US households was over 30% in 2011 and estimated at 23% in 2009, making the sector one of the fastest growing segments in the household industry (ENERGY STAR, 2011).

A leading tool to assess environmental performance is life cycle assessment (LCA), a method defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b). LCA is an internationally recognized approach that evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, production, use, and end-of-life treatment. LCA may be used to identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication and awareness-building efforts.

It is important to note that LCA estimates relative potential impacts—limitations that are clearly indicated and accepted in the ISO 14040 series of LCA standards—rather than directly measuring real impacts. Despite these limitations, the concept and need for LCA are sufficiently strong that over the past several decades it has become the principal approach to evaluate a broad spectrum of environmental problems and help optimize the entire sustainability equation. Moreover, LCA is the industry standard for measuring and communicating sustainability.

PAC, Packaging Consortium, a North American not-for-profit corporation, was founded in 1950 and has since become a major voice for the North American packaging industry, driving progressive change in the packaging value chain through leadership, collaboration and knowledge sharing. One of PAC's core products is the PAC FOOD WASTE initiative that has a vision to be a *catalyst for food waste packaging solutions* by maximizing the reduction of food waste through packaging solutions that consider strategic retail trends, supply chain implications, life cycle thinking and ecodesign (PAC, 2014).

One of PAC's three inaugural projects for the PAC FOOD WASTE initiative aims to better understand the relationships between North American packaging and the causes of food waste along the food value chain through an LCA of coffee systems that differ mainly in their packaging systems.

To shed light on the environmental performance of different coffee systems, Quantis was commissioned by PAC to conduct a formal ISO compliant LCA study comparing the environmental performance of single-serve coffee (i.e. a capsule system) and bulk coffee (i.e. a drip-brewed system).

This full LCA was conducted using both primary data from Mother Parkers Tea & Coffee and generic data and considered market-leading single-serve brewers with market-leading coffee capsules, whereas the bulk coffee brewing system results are based on a standard set-up, including the drip filter coffee machine, paper filter and bulk coffee packaging (can and pouch). These data can therefore be used to compare the relative environmental impacts associated with 1) brewing one cup of coffee using a market-leading single-serving capsule and 2) brewing coffee using bulk coffee and a standard drip filter coffee machine.

This LCA should comply with the International Organization for Standardization (ISO) 14040 and 14044 standards (ISO 2006a; ISO 2006b) for public disclosure and was peer-reviewed as a requirement of the ISO LCA standards for the public disclosure of comparative assertions.

2 Goal of the study

This section describes the goal and scope of the study, along with the methodological framework of the LCA. It includes the background and context for this study, the objectives, a description of the product function and product system, the system boundaries, data sources and methodological framework. This section also outlines the requirements for data quality and the review of the analysis.

2.1 Objectives

This study evaluates two coffee systems: 1) single-serve coffee and 2) bulk coffee brewing (drip-brewed).

The specific goals of this study are to:

I. Establish credible and transparent profiles of the potential life cycle environmental impacts of a single-serve coffee system and of a bulk coffee brewing system by utilizing appropriate databases and accepted LCIA characterization factors and identify the contribution of the different life cycle stages;
II. Identify the magnitude and confidence of the comparative environmental advantages of the studied systems;
III. Identify key data points, uncertainties and methodological choices that might influence comparisons
IV. Ensure that the study complies with the ISO 14044 standards.

This study will provide comparative statements regarding the environmental performance of the two aforementioned systems.

2.2 Intended audiences

The project report is intended to provide results in a clear and useful manner to inform PAC of the environmental performance of the studied systems and may be used for disclosure to external audiences. The results and conclusions presented in this report are subject to a critical review process and may be communicated publicly. According to ISO standards, a critical review of an LCA is mandatory if its results are to be communicated publicly (section 4.10).

2.3 Disclosure and declarations

PAC seeks to evaluate and compare the environmental performance of a single-serve coffee to that of bulk coffee brewing. The project complies with the ISO 14040 and 14044 standards for reports with comparative assertions intended to be disclosed to the public. The only comparisons intended for this study are between the two evaluated scenarios and between life cycle stages and processes within the life cycle of a specific coffee system.

3 Scope of the study

3.1 General description of the studied product systems

Figure 1 illustrates the two studied coffee systems.

Figure 1: Studied coffee systems

The two studied coffee systems have many common components:

- Arabica coffee from Brazil is considered for both scenarios.
- The single-serve capsule's filter and the standard no.4 paper filter for drip-brewed coffee are both made out of abaca fibres.
- Direct retail (e.g. supermarket) is considered for both scenarios (Mother Parkers, 2014).
- For both systems, a ceramic mug of 250 ml capacity (mass of 300 g) is considered to be washed after every use and is assumed to have a service life of 500 use cycles.

3.2 Comparative basis

3.2.1 Functions and functional unit

Life cycle assessment relies on a functional unit as a reference to evaluate the components within a single system and or among multiple systems on a common basis. It is therefore critical that this parameter be clearly defined and measurable. The main function of the different products is to *provide filtered coffee with two coffee systems*.

The functional unit—the quantitative reference used for all inventory calculations and impact evaluations—is:

Provide one 8-oz. serving of filtered coffee from single-serve coffee and from drip-brewed coffee for the North American market

The single-serve coffee system and the drip brewed coffee system with a drip filter machine fulfill the functional unit and are assessed in this project. There may be other types of coffee systems that fulfill this functional unit, such as an espresso machine system, a pad filter system or spray dried soluble coffee with boiler system. These alternative systems are not addressed in this study. Also, although the flavor, mouth feel and overall taste experience of coffee may differ between single-serve and bulk coffee, these aspects will not be covered by the LCA, and the two scenarios are assumed to be functionally equivalent.

Furthermore, consumer behaviours are a key parameter that can affect the way the coffee machine is used throughout its service life (e.g. efficient vs. non-efficient use of the machine) as well as the amount of coffee that is consumed or wasted over a certain period of time. Unfortunately, few reliable studies or surveys on consumer behaviours were identified in this study. Only the assumptions on usage frequency and average use of the warming plate are based on a national survey of US consumers (ENERGY STAR, 2011). Other parameters describing consumer behaviours such as coffee waste are based on assumptions from a previous peer-reviewed article (Humbert et al. 2009) or made by Quantis and PAC. For this reason, certain variations between the two coffee systems, including consumer behaviours, will be assessed in different scenarios or sensitivity analyses. More specifically, variations of the four following behaviour parameters were considered:

1) **Efficiency and ready-to-serve mode**: The efficiency of a single-serve brewer depends on the type of heater, parts insulation and available features. Flow-type heaters are the most efficient water heaters for coffee machines. This type of brewer is activated only for coffee brewing and switched off immediately when coffee production is finished (Nipkow, 2011) and therefore does not require an auto-power down feature. Brewers may also feature a ready-to-serve mode, which is a pre-heat function requiring that the brewer be equipped with a reservoir of water that is permanently kept at 85°C to 90°C for immediate production. An eco mode may also be available on certain brewers, making it possible to lower the temperature at which the water is kept in the reservoir.

2) **Coffee waste due to overpreparation**: For drip-brewed coffee, the amount of coffee prepared is not always accurate and to avoid the situation in which the consumer has not prepared enough coffee, the consumer tends to prepare a bit more than necessary. Part of the coffee is therefore prepared in addition to the intended amount, which is referred to as a coffee waste due to over-preparing. The additional amount of coffee prepared is considered to be, in the worst case, 50% of the intended amount. For example, 50% waste means that for 4 cups of coffee consumed, 6 cups are actually prepared.

3) **Coffee waste due to inferior freshness retention**: Unlike single-serve capsules, which conserve their freshness up until they are inserted in the brewer, drip-brewed coffee is packaged in bulk and therefore consumed over a longer period of time, which ultimately affects the freshness of the product. Consequently, the consumer may discard a certain amount of coffee before it is consumed in its entirety, which is referred to as coffee waste due to inferior freshness retention. The amount of coffee discarded is considered to be, in the worst case, 30% of the coffee contained in the packaging.

4) **Period of use of the keep-warm mode**: Drip-filter brewers usually feature a warming plate to keep the coffee warm for a certain period of time following its preparation. Certain machines will have an auto-power down feature that minimizes the keep-warm time while other machines or consumers will leave the hot plate active for a long period.

These behaviours are considered in the definition of a series of scenarios that will be assessed. These scenarios are presented in Table 1.

Table 1: Study scenarios

System 1 **Single-serve coffee**	System 2 **Bulk coffee brewing (drip-brewed)**
S1a Single-serve, efficient One serving of single-serve coffee using a flow-type heaters: BEST CASE [1] (Quantis assumed the coffee machine model based on Nipkow (2011))	**S2a Drip-brewed, accurate** One serving of drip-brewed coffee for an accurate amount of coffee and no coffee waste, heated with a hot plate for 37 minutes: BEST CASE[2]
S1b Single-serve, ready to serve feature One serving of single-serve coffee using a brewer with a ready-to-serve feature: WORST CASE (Quantis assumed the coffee machine model based on European Commission (2011))	**S2b Drip-brewed, 50% coffee waste, overpreparation** One serving of drip-brewed coffee with a 50% waste due to over-preparing (Quantis assumed 50% waste based on Humbert (2009))
	S2c Drip-brewed, 30% coffee waste, loss of freshness One serving of drip-brewed coffee for an accurate amount of coffee and 30% coffee waste due to inferior freshness retention (Quantis and Mother Parkers assume 30% waste)
	S2d Drip-brewed, 50% coffee waste overconsumption, 30% coffee waste loss of freshness, 2 hours of heating One serving of drip-brewed coffee with 50% waste due to over-preparing and 30% coffee waste due to inferior freshness retention, heating with a hot plate for 2 hours[3]: WORST CASE (Quantis assumed keep-warm times based on ENERGY STAR (2011))

[1] The single-serve scenario considering a flow type heater represents the scenario with the lowest energy consumption and will be considered as the reference scenario and best case for the single-serve coffee system.

[2] For the drip-brewed coffee system, the reference scenario will also represent the best case, in which no coffee is wasted throughout the entire life cycle and in which the drip-filter coffee maker's hot plate is used for 37 minutes (average use based on ENERGY STAR 2011).

[3] Sensitivity analyses will also be conducted for different coffee waste % due to overpreparation, lack of freshness % and keep-warm times than those considered in the studied scenarios.

Detailed data and assumptions for the studied systems are presented in section 4.2.1.

3.2.2 Reference flows

To fulfill the functional unit, different quantities and types of material and packaging are required for each system. These are known as reference flows. The main reference flows for the studied systems are the following:

Table 2: Main reference flows

Material	Scenario 1 Single-serve coffee	Scenario 2 Drip-brewed coffee
Coffee (g)	S1a: 10 S1b: 10	S2a: 10 S2b: 15 S2c: 13 S2d: 18
Capsule (unit)	1	--
Filter (unit)	--	1/4
Packaging weight[1] (g)	Capsule filter: 0.28 Capsule lid: 0.25 Capsule shell: 2.68 Capsule nitrogen: 0.43 Fraction of 12-pack box: 2.76	Filter packaging: 0.063 S2a: Coffee pouch: 0.24 S2a: Coffee can: 0.81 S2a: Coffee pouch: 0.24 S2b: Coffee can: 0.81 S2b: Coffee pouch: 0.36 S2c: Coffee can: 1.06 S2c: Coffee pouch: 0.31 S2d: Coffee can: 1.47 S2d: Coffee pouch: 0.43
Distribution weight (g)	17.9	S2a: 11.3 S2b: 16.9 S2c: 14.7 S2d: 20.2
Brewer (unit)	0.0005	0.0005
Mug (unit)	1/500	1/500
Electricity consumption for dishwashing (Wh)	30	36
Electricity consumption for coffee preparation and keep-warm mode (Wh)	S1a: 34 S1b: 70	S2a:59 S2b: 76 S2c: 59 S2d: 131
End-of-life of coffee (used or lost due to freshness) (g)	S1a: 10 S1b: 10	S2a: 10 S2b: 15 S2c: 13 S2d: 18
End-of-life packaging weight[2] (g)	6.0	S2a: 1.1 S2b: 1.6 S2c: 1.4 S2d: 2.0

[1] Packaging weights presented in this table do not include production losses.
[2] Includes packaging that ends up at consumer. Capsule tertiary packaging and filter and bulk R&G coffee secondary and tertiary packaging represent a small amount of packaging and are not shown in this total. Their end-of-life impacts were, however, compiled in this study.

3.2.3 General description of the system

This study assesses the life cycle of brewing coffee using single-serve capsules or bulk coffee, from the extraction and processing of all raw materials to the end of life of the coffee and its packaging system. In the case of the single-serve capsule, it is modeled to represent a generic capsule that uses a traditional abaca filter based on current designs. In the case of the drip-brewed coffee system, it is modeled to represent a generic no. 4 filter that uses a traditional abaca filter and based on current designs and packaging as well as a generic bulk coffee packaging system based on current designs. The system boundaries identify the life cycle stages, processes, and flows considered in the LCA and should include all activities relevant to attaining the above-mentioned study objectives. Therefore, it is necessary to provide the specified function. The following paragraphs present a general description of the two systems as well as the temporal and geographic boundaries of this study.

As illustrated in Figure 2 and Figure 3, the systems are divided into five principal life cycle stages: (1) coffee supply, (2) materials and production, (3) distribution, (4) use and (5) end of life.

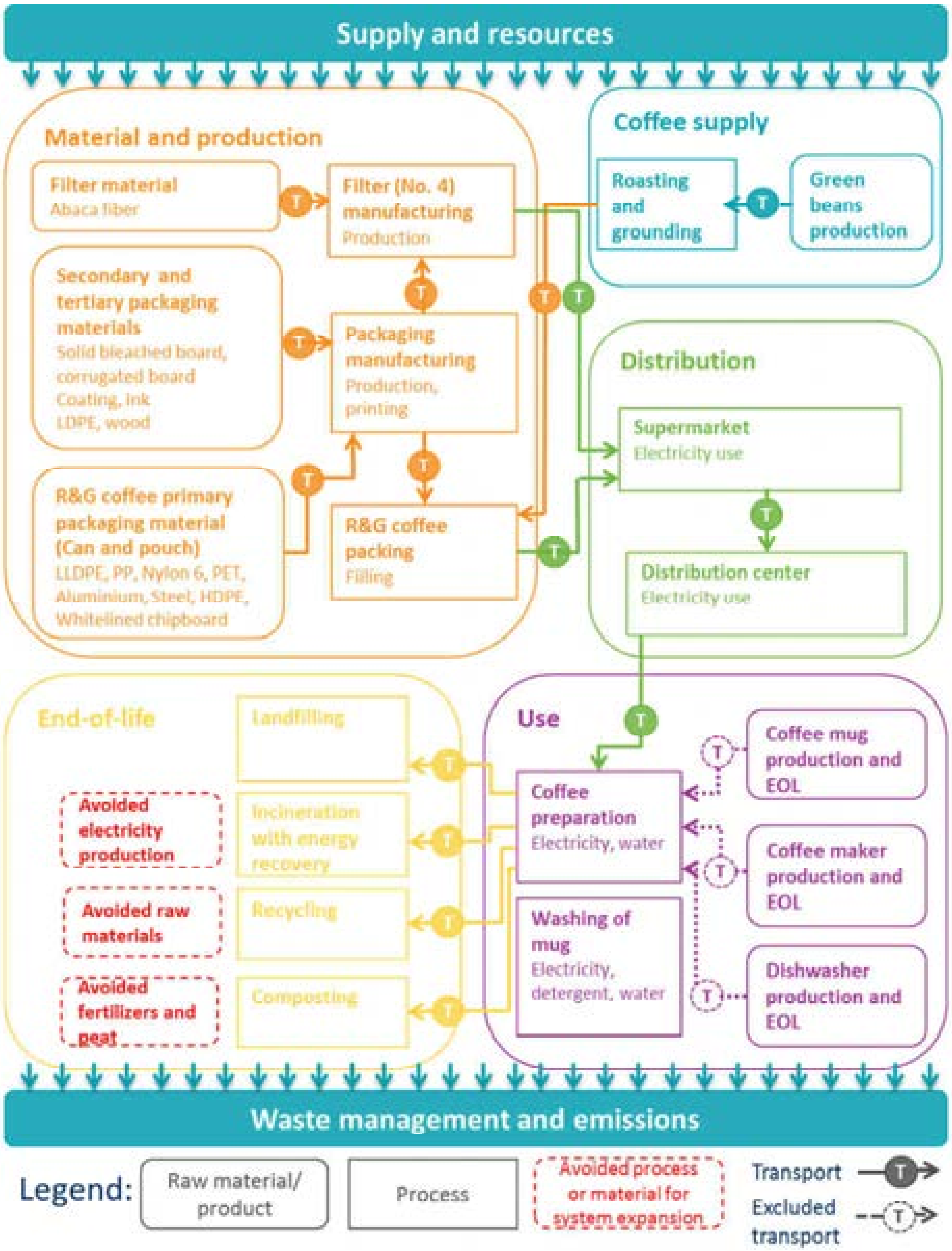

Figure 2: Life cycle of a serving of drip-brewed coffee

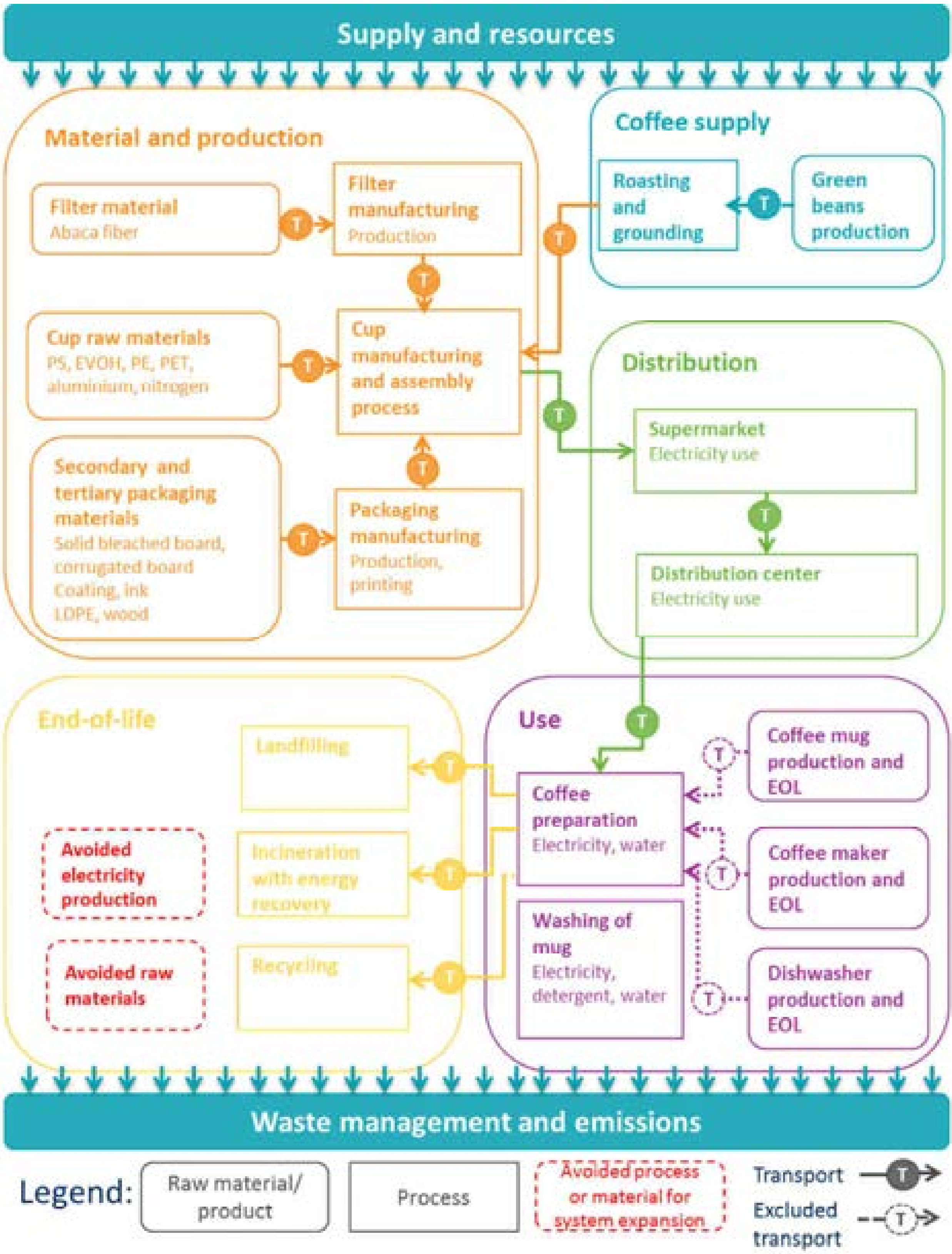

Figure 3: Life cycle of a serving of single-serve coffee

Within each of these stages, the LCA considers all identifiable upstream inputs to provide as comprehensive a view as is practical of the product system. For example, when considering the environmental impact of transportation, not only are the emissions of the truck considered but the impacts of the additional processes and inputs needed to produce the fuel are also included. The production chain of all inputs is therefore traced back to the original extraction of raw materials.

The study focused on the life cycle of a serving of coffee based on two coffee making systems. All system components and production processes were included using either readily available information or a reasonable estimate. In cases in which important information was unknown, uncertain or highly variable, sensitivity analyses were performed to evaluate the potential significance of the data gap(s) or data influence (see section 5 for details).

3.2.4 Life cycle stages

For the purposes of this analysis, the system was grouped into the following principal life cycle stages.

1) **Coffee supply**: pertaining to the raw and secondary materials required to manufacture coffee. For instance, it includes the green coffee cultivation, coffee roasting and grinding, etc.
2) **Materials and production**: including the transport and production of the capsule components (lid, outer shell, filter, etc.), the standard no. 4 filter from abaca paper, the bulk R&G coffee primary packaging as well as secondary and tertiary packaging for the capsules, standard filter and bulk coffee packaging.
3) **Distribution**: including all stages of transport and storage related to the capsules, filters and bulk coffee from the manufacturing plant to the distribution center and then to the retailer. The distance and mode scenarios were kept equivalent between systems, but since the different packaging systems vary in weight, the impact of their transport is not equivalent.
4) **Use**: including the energy required for coffee preparation (water heating for a temperature difference of 70°C) for both the single-serve brewer and the drip filter coffee machine. Energy for the use of a hot plate is also considered for the drip filter coffee machine. Also included in this stage for both scenarios is the manufacturing of the coffee brewers and coffee mug as well as the washing of the mug. For the drip-brewed scenario, the washing of the decanter was also considered.

5) **End-of-life**: including the activities associated with the waste management of coffee and packaging. The capsule and the standard no.4 filter are assumed to be disposed of at the end of their service life, to be picked up at curbside and sent to the landfill or incineration site based on North American waste management statistics. Filter and coffee packaging (primary, secondary and tertiary) and capsule packaging (secondary and tertiary), if recyclable, are considered to be recycled at average North American residential rates. For the drip-brewed coffee system, 3.9% of households will compost the used coffee grounds instead of putting them in the garbage, based on the average percentage of food waste that is composted in the US (EPA, 2011).

The **supply and resources** sub-system pertains to resource procurement (water, energy, chemicals and materials) including the extraction, treatment and transformation of natural resources and transport to use sites (e.g. polymers, fuels, etc.).

Finally, the **waste management and emissions** sub-system pertains to activities associated with the transport and treatment of waste generated (e.g. procurement, production of virgin material and distribution) and emissions to air, water and soil over the considered life cycle stages.

3.2.5 Temporal and geographic boundaries

This LCA is representative of the coffee industry and associated processes in North America at the time the study is conducted (2014). The data and assumptions are intended to reflect current equipment, processes and market conditions for distribution and retail. It should be noted, however, that certain processes within the system boundaries may take place anywhere or anytime. For example, the processes associated with the supply chain and waste management may take place in Asia, North America or elsewhere in the world. In addition, certain processes may generate emissions over a longer period of time than the reference year. This applies to landfilling, which causes emissions (biogas and leachate) over a period of time whose length (several decades to over a century/millennium) depends on the design and operation parameters of the burial cells and how the emissions are modeled in the environment.

3.2.6 Cut-off criteria

Processes or elementary flows may be excluded if their contributions to the total system's mass or energy flow or environmental impact are less than 1%. All product components and production processes are included when the necessary information is readily available or a reasonable estimate can be made. It should be noted that the capital equipment and infrastructure available in the ecoinvent database is included in the background data (e.g. data indirectly involved in the model) for this study in order to be as comprehensive as possible.

Based on Quantis' past experience and previous studies (e.g. Humbert et al. 2009) or the relatively low contribution of the life cycle sub-stages to which they pertain, the following processes are excluded from the study due to their contribution, which is expected to be lower than the cut-off criteria, and the lack of readily available data:

- Packaging of the green coffee
- Packaging of bulk raw materials (e.g. plastic sheet roll stock)
- Glue on cardboard and paper packaging
- Activities linked to the insertion into the capsules are excluded from the study
- Sealing of the lids onto the capsules
- Fuel for lift and other mechanical support used during storage
- Distribution and purchase trip for the coffee machine
- Distribution and packaging of the mug
- Cleaning and decalcification agent for machine other than detergent (limescale remover or similar) as well as the distribution and packaging of the detergent
- Other kitchenware (spoon) or ingredient (sugar, milk, etc.)

4 Approach

4.1 Allocation methodology

A common methodological decision point in LCA occurs when the studied system is directly connected to a past or future system or produces co-products. This occurs at production (e.g. abaca cultivation yields biomass, co-product of pulping process), manufacturing (e.g. energy use and fuel use are aggregated at the plant level for many production lines) and at end of life (e.g. energy recovery during the incineration of the different coffee packaging components). When systems are linked in this manner, the boundaries of the system of interest must be broadened to include the adjoining system or the impacts of the linking items must be distributed—or allocated—across the systems. While there is no clear scientific consensus on an optimal method to handle this in all cases (Reap et al. 2008), many possible approaches have been developed, and each may have a greater level of appropriateness in certain circumstances.

ISO 14044 prioritizes the methodologies related to applying allocation. It is best to avoid allocation through system subdivision or expansion. If that is not possible, then allocation using an underlying physical relationship should be carried out. If using a physical relationship is not possible or does not make sense, another relationship may be used.

4.1.1 Incineration with energy recovery

An allocation decision must be made regarding the additional functions provided by incineration such as energy recovery, which, by definition, provides an energy source for use by another system. The electricity produced by the incineration of capsules and standard no. 4 filters will be used by another (receiving) life cycle, which may be one of thousands industrial processes. The flow of energy must be allocated (shared) between the emitting and receiving product systems. The flows for each system are modeled according to the system expansion approach, as described in Table 3. This is represented as the net values of the inventory flows associated with the treatment process (i.e. incineration) and credited (negative) inventory flows associated with the production of conventionally-generated energy (electricity).

Table 3: Summary of end-of-life modeling of the different coffee packaging components

	Impact	Credit
Landfill	Paper and plastics	None
Incineration	Paper and plastics	Electricity generation

It is important to note that no allocation was made in the foreground processes (i.e. processes directly linked to the studied system). For every multi-output case, the multifunctionality was covered by a system expansion of the boundaries, in keeping with the study objectives. Thus, in the case of waste-to-energy incineration, a functional equivalence was ensured by including the production of electricity. The electrical energy recovered from incinerated waste varies according to the type of material incinerated, as presented in Table 4.

Table 4: Waste electric energy from material incineration (SCLCI, 2010)

Material incinerated	Coffee packaging component	Waste electric energy (MJ/kg)
Aluminum	• Capsule lid • Bulk coffee can with peelable lid and body • Bulk coffee pouch	0
Packaging cardboard	• Primary, secondary and tertiary packaging	1.55
Paper, abaca filter	• Capsule filter • Standard no.4 filter	1.32
Plastics mixture	• Capsule shell • Bulk coffee pouch	3.48
PE	• Standard no.4 filter bags • Shrink wrap	5
PP	• Bulk coffee can and pouch valve	3.74
Steel	• Bulk coffee can rim and bottom	0
Tin	• Bulk coffee pouch tie	0
Wood	• Pallets	1.3

Although takeback initiatives exist for recycling of capsules and composting of coffee grounds (Nespresso, 2014; Keurig, 2014), the majority of used capsules end up in the waste stream. For the purposes of this study, it was assumed that once a material is sent to disposal, 81% (by mass) of waste is sent to landfill and 19% is sent to incineration with energy recovery (USEPA, 2011).

4.1.2 Recycling

Single-serve capsules, standard no. 4 filters and bulk coffee waste are considered to be thrown out after use. Primary, secondary and tertiary filter packaging as well as bulk coffee secondary and tertiary packaging are considered to be recycled at average North American residential rates (see Table 6 for details). As for R&G coffee packaging, only the plastic lid of the can is considered to be recycled since the composite can and pouch are considered to be non-recyclable. In order to avoid allocation when modeling recycling, the expansion boundary approach was used, meaning that materials recycling contributes to avoiding the production of virgin materials and accounts for the impact of the recycling process itself. Table 5 presents a list of recycled materials and associate virgin materials avoided.

Table 5: Recycling modeling using system expansion

Recycled material	Recycling inputs	Avoided virgin material[1]
Cardboard box	Corrugated recycled fibre	Core board
Corrugated box	Corrugated recycled fibre	Core board
PE wrapping	Electricity (N-Am) 0.6 kWh	HDPE

[1]Recycling inputs and avoided materials were selected based on ecoinvent DB recommendations for recycled materials

4.1.3 Freight transport

As seen in Figure 2 and Figure 3 on system boundaries, the impact of transporting the different coffee system components and their packaging is included in this study. While component and raw materials transport options are treated distinctly for the different systems based on the supplier's location and assumptions, it was not possible to obtain sufficient information on the distribution profile of different marketed capsules. Moreover, the distribution profile of single-serve capsules production facility to consumers is dependent on market share and size (e.g. network of distribution centers) and consumer behaviours (e.g. online versus retail). Because of the high variability and uncertainty associated with the distribution stage of the two studied systems, distance and transport modes were considered identical.

It is important to note that volume limited transportation was considered for several transport stages in the current study.

4.1.4 ecoinvent processes with allocation

Many of the processes in the ecoinvent database also provide multiple functions, and allocation is required to provide inventory data per function (or per process). This study accepts the allocation method used by ecoinvent for these processes. It should be noted that the background allocation methods used in ecoinvent, such as mass or economic allocation, may be inconsistent with the approach used to model the foreground system. While this allocation is appropriate for foreground processes, the continuation of this methodology into the background datasets would add complexity without substantially improving the quality of the study.

4.2 Life cycle inventory

The quality of the LCA results depends on the quality of the data used in the evaluation. Every effort was made to rely on the most credible and representative information available in this study.

4.2.1 Data sources and assumptions

4.2.1.1 Primary and secondary data

Life cycle inventory (LCI) data collection mainly pertains to the materials used, the energy consumed and the waste and emissions generated by each process included in the system boundaries. Primary data was collected directly from Mother Parkers or from direct measurements for the primary materials and material weights and data related to transportation distances, modes and efficiency.

Additional information describing the remaining aspects of the life cycle was collected from a variety of publications and experts and especially studies published by the Food and Agriculture Organization of the United Nations (FAO), the US Environmental Protection Agency (USEPA), ENERGY STAR and scientific journal articles. Several parameters were sourced from Quantis' internal guidelines, which are based on published and confidential sources as well as expert estimations.

All life cycle inventory data sources were taken from the ecoinvent database v2.2 (SCLCI 2010), which is the main source for secondary LCI data. It should be noted that most, though not all, of the data in ecoinvent is of European origin and produced to represent European industrial conditions and processes. Therefore, several modules were adapted in order to enhance their representativeness of the studied products and contexts. Consequently, for all the activities related to abaca that take place in a specific geographic context, the ecoinvent modules were adapted by replacing the European electricity grid mix with a more representative one:

- As an estimate, abaca harvesting and pulping processes use grid mixes from Asian countries. The production of abaca fibres uses an Indian grid mix for certain foreground processes (i.e. processes directly linked to the studied system), while the pulping processes use an estimated Thailand grid mix;
- Abaca filter production uses the grid mix for the UK, where the facility is located;
- An average North American grid mix was used for foreground and background processes for the manufacturing of the capsule, standard no.4 filter and bulk coffee can and pouch. This mix represents an average of the different electricity mixes associated with the production locations of the different competing brands;
- The North American grid mix was used for background processes (i.e. all processes directly or indirectly related to foreground processes). In this case, since procurement for the various stages of the life cycle may not only occur in Canada, the North American grid mix was more appropriate. For example, all foreground processes occurring at capsule manufacturing facilities (e.g. shell cutting) required background processes that were adapted to the North American energy context.

The data's geographic representativeness was taken into account as part of the data quality assessment.

4.2.1.2 Key assumptions

The following key assumptions were made in the LCA model:

Table 6: Data and assumptions

Life cycle stage	Scenario 1: single-serve coffee	Scenario 2: Drip-brewed coffee
Coffee supply	• The capsules are used to deliver coffee or tea of many different types and flavours. Thus the numerous varieties of coffee and tea that may be contained in the capsules are considered to be outside the boundaries of the study. Only a generic type and amount of coffee is considered in the full life cycle analysis to estimate its importance. • Green coffee production is considered to be identical to the production described in Coltro et al. (2006) and Humbert et al. (2009a), and roasting and grinding is as described in De Monte (2003). • The single-serve capsule contains 10 g of coffee (Mother Parkers, 2012). • The preparation of an accurate serving of drip filter coffee requires 10 g of coffee (Mother Parkers, 2014).	
Materials and production	**Capsule production:** • The studied capsule uses a typical filter of abaca fibres and is composed of a multi-layer polystyrene based shell and a multi-layer aluminium lid. • The studied conventional capsule is the leading design on the market and may be used with any Keurig single-serving brewer or other compatible coffee machines. • To prevent coffee oxidation, nitrogen is injected into single-serve capsules. • Capsule components, materials and weights are presented in Table 7. • An electricity consumption of 0.00288 kWh was used to model shell production by thermoforming, lid cutting, shell cutting, assembly, use of conveyors, filling and packing (Mother Parkers, 2012). • Shell composition was assumed to be 94.1% PS, 4.3% PE and 1.6% EVOH (Mother Parkers, 2012). The processing of shell plastic sheet was modeled by using generic ecoinvent processes such as extrusion plastic film. • Lid composition was assumed to be 57.9% PE, 28.5% Al foil and 13.6% PET (Mother Parkers, 2012). • Processes for lid production were modeled by using generic ecoinvent processing such as sheet rolling, calendaring as a proxy for lamination of aluminum with PET and HDPE, printing and die cutting. • The printing area considered per lid is 19.6 cm^2 (Mother Parkers, 2012). Ink requirements were estimated at 0.038 g using an ecoinvent color print with an offset printer (Quantis assumption).	**Filter production and packaging:** • The studied filter for drip filter coffee preparation is a typical no.4 filter of abaca fibres weighing 0.9 g (Quantis measurement). • The filters are cut and packed at the filter production facility, which is considered to be located in North America. • The boxed filters are marketed in a box made of solid bleach board. A 19% packaging production loss is considered (Quantis assumption), which is sent to a recycler. They filters are distributed in the same shipment box as the single-serve 12-packs with the same pallet and same amount of LDPE shrink wrap. The shipment box fits 18 boxes of 40 filters and 9 boxes of 100 filters (Quantis assumption, based on calculations). • The bagged filters are marketed in a bag made of HDPE. A 19% packaging production loss is considered (Quantis assumption). The filters are distributed in the same shipment box as the single-serve 12-packs with the same pallet and same amount of LDPE shrink wrap. The shipment box fits an estimated 100 bags of 100 filters and 50 bags of 200 filters (Quantis assumption, based on calculations). • Table 8 presents the formats and weights of the filter packaging options. **R&D bulk coffee packaging:** • R&G bulk coffee is packaged in cans or pouches. A 19% packaging production loss is considered for the can and pouch options (Quantis assumption).

Table 6: Data and assumptions

<table>
<tr><th>Life cycle stage</th><th>Scenario 1: single-serve coffee</th><th>Scenario 2: Drip-brewed coffee</th></tr>
<tr><td></td><td>
• Lids supplied to the capsule production facility were assumed to be precut, preprinted and packaged in cartons (1 000 units/carton) and corrugated shipment boxes (18 cartons/box) based on supplier information for a similar product (Alibaba, 2012).

Capsule packaging:

• The studied capsule is marketed in a 12-unit box made of solid bleach board weighing 33.13 g (Quantis assumption and measurement). A 19% packaging production loss is considered for the box (Quantis assumption), which is sent to a recycler.
• Tertiary packaging includes a corrugated shipment box weighing 145.04 g that fits six 12-unit boxes, LDPE wrapping weighing 150 g and a wood pallet weighing 26.2 kg that fits 120 boxes (8 640 capsules) (Mother Parkers, 2012).
• The service life of the pallet is assumed to be 50 years.
</td><td>
• The pouch is a 4-ply structure: 0.48 mil PET / ink / adhesive / 0.35 mil Foil / adhesive / 0.48 mil PET / adhesive / 3 mil PE (Mother Parkers, 2014).
• Coffee cans are distributed on a corrugated shipment tray weighing 119 g that fits 6 cans with 30 g of LDPE shrink wrap per tray. Tertiary packaging for the cans includes a wooden pallet that can hold 49 trays and 88 g of shrink wrap (Mother Parkers, 2014).
• Coffee pouches are distributed on a corrugated shipment box weighing 300 g that fits 12 pouches. Tertiary packaging for the pouches includes a wooden pallet that can hold 60 boxes and 88 g of shrink wrap (Mother Parkers, 2014).
• Table 9 presents the bulk packaging formats and weights.
</td></tr>
<tr><td>Materials and production</td><td colspan="2">
Abaca and pulp production for filters:

• Abaca production is considered to be 14% from Ecuador and 86% from the Philippines. Based on FAO statistics, the average production share of abaca from 2004 to 2010 is 14% Ecuador, 83% Philippines and 3% other countries (FAO 2010). Since abaca from countries other than Ecuador and the Philippines are unknown and of little importance, the share was modeled as a Philippines production (Quantis assumption).
• A correction factor was applied to take into account differences in yield between jute and abaca production. Average yields are considered as follows: jute 1.8 T/ha; abaca from Ecuador 1.4 T/ha (El Telégrafo, 2012); abaca from the Philippines 0.53 T/ha (Bureau of Agricultural Statistics, 2009). To the authors' knowledge, Abaca production yield in Ecuador is not available from FAO documents or other publications by the Ecuadorian government. However, an online publication from the Bureau of Agricultural Research of the Republic of the Philippines states that the Ecuador yield ranges from 1 to 1.5 T/ha (Cuevas, 2002), which is coherent with the selected yield reported by a local Ecuadorian newspaper.
• A 60% rate for mechanical abaca harvesting in the Ecuador and 10% in the Philippines were estimated. The Philippines production is mostly done manually, while some mechanical support is used in Ecuador (CFC/UNIDO/FIDA, 2009).
• Fuel and water consumption to operate mechanical decorticators were taken for a technical document based on a field trial (UNEP, 2009).
• Pulp mills were considered to be local and located near an important port in Philippines (Cebu region) and Ecuador (Guayaquil). Pulp is then sent to the filter production facility, which was assumed to be located in Lydney, UK (Quantis assumption based on research).
• Transport within Ecuador and the Philippines is based on estimated distances from the most probable plantations, ports and facilities (Quantis assumption based on research).
</td></tr>
</table>

Table 6: Data and assumptions

Life cycle stage	Scenario 1: single-serve coffee Scenario 2: Drip-brewed coffee
	• Transport of abaca pulp to the filter production facility was assumed to be by freight ship and truck (Quantis assumption based on research). • A small distance (2 km) of tractor use was estimated for displacement within the Philippines farms (Quantis assumption). • The ecoinvent process *sulphate pulp, from eucalyptus, unbleached, at pulp mill in Thailand* was used to approximate abaca pulp production in the local context by substituting eucalyptus fibre with abaca fibre. A yield of 70% was used to model the pulping of abaca fibre (Jiménez, E. et al., 2005). • Composition of abaca filter was assumed to be: abaca 72%, wood pulp 8%, PE 20% (HunterConsult Incorporated, 1997; Mother Parkers, 2012). • HDPE was used to model polyethylene since it is a form of PE often used in the food industry (PlasticEurope, 2010). Film extrusion was used as a proxy for the processing of HDPE granulates. • The process for production of Kraft paper was used as a proxy for the wet laid process, which is similar to paper production except that it is made from synthetic fibres blended with the natural fibres (Edana, 2008). Thus, the processes for paper production would account for the abaca filter production step. • The *Kraft paper, bleached, in Europe* database process was adapted to approximate the abaca portion of the filter and was modified by substitution of softwood by abaca pulp. Pulp to paper ratio for abaca was assumed equivalent to softwood's. • 5% losses were assumed for abaca filter production (Quantis assumption). • The supply of filters to the capsule production facility was assumed to be precut and packaged in cartons (1 000 units/carton) and corrugated shipment boxes (18 cartons/box). No data were available for filter supply packaging. Thus, these reference flows were calculated based on lids supply packaging. • The supply of no. 4 filters to the filter production facility was assumed to be shipped in roll stocks (Quantis assumption). • The energy requirements for die cutting were estimated based on technical information on a YIZHAN Model ZBS-350 machine assuming 75% of power in operation (Quantis assumption). It was assumed that one punch cuts 100 filters at once (Quantis assumption).
Distribution	• Direct retail (e.g. supermarket) is considered for both scenarios (Mother Parkers, 2014). • Truck transport is modelled using ecoinvent v2.2 with data adaptation for a North American context. • Storage time in distribution centre is considered to be of 3 months on average (Quantis assumption) for capsules, bulk coffee and coffee filters. Shelving duration for capsules, bulk coffee and coffee filters is considered to be of 1 month on average. • The average electricity consumption for storage and shelving at distribution centres and supermarkets is 6 kWh/m3·yr and is based on Quantis internal knowledge. • For transport from the manufacturing facility to the distribution centre, a transport distance of 1 007 km was considered for both scenarios and is based on single-serve manufacturing plants and warehouses locations (Quantis assumption based on research). It was assumed that 60% of the transport is by freight train and 40% by truck (Quantis assumption). • For the transport from the distribution centre to the supermarket, an average transport distance of 720 km was considered. This distance is based on Quantis internal knowledge. Transport is by truck only (Quantis assumption). • For the transport of the products from the supermarket to the consumer's home, an average distance of 11 km by car and a 5% allocation per product is considered based on Quantis internal knowledge.

Table 6: Data and assumptions

Life cycle stage	Scenario 1: single-serve coffee	Scenario 2: Drip-brewed coffee
Use	• Usage frequency of single-serving brewer is assumed to be 275 coffees per year based on US use profiles (ENERGY STAR, 2011). • Bill of material and service life of the brewer is assumed to be similar to the hard cap espresso maker (European commission, 2011), which is estimated at 7 years (ENERGY STAR, 2011). It is assumed that manufacturing and assembly occur in China (Quantis assumption). A sensitivity analysis on machine service life will be conducted. • The brewer considered in scenario 1.a) is assumed to have a flow-type heater, the most efficient water heaters for coffee machines. This type of brewer is activated only for coffee brewing and switched off immediately when coffee production is finished (Nipkow, 2011) and therefore does not require an auto-power down feature. Electricity consumption includes warm-up only, for a temperature difference of 70°C. Measured values according to TopTen-measurements (Josephy, 2011) range from 8.1 to 14.7 Wh for 80 ml of heated water. Median value was used to model energy consumption. No ready-to-serve mode (i.e. the water is kept hot for immediate production), standby mode (i.e. electronics and display are active) or off mode (i.e. the machine is inactive but is not out of tension, where residual electricity consumption usually occurs over long periods of time) were considered for this scenario. • Scenario 1.b) represents the use of a coffee machine with an additional feature, the ready-to-serve mode. The brewer that is considered includes a pre-heat feature, which consists of a reservoir of water kept at 85°C to 90°C for immediate production as long as the ready-to-serve mode is activated. It was assumed that the auto-power-down feature and the eco mode that reduces the temperature that the water is kept at in the reservoir are not used by the consumer. The energy consumption to initially get the water to 85°C to 90°C is the same as for the scenario 1.a) brewer. The ready-to-serve mode is assumed to consume 10 W and used on average 11 hours a day when considering 3 coffees of 240 ml a day (European Commission, 2011). A sensitivity analysis on the ready-for use mode duration will be performed. • A ceramic mug of 250 ml capacity (mass of 300 g) is considered to be	• Usage frequency of drip filter coffee machine was assumed to be 338 coffees per year based on US use profiles (ENERGY STAR, 2011). • Each preparation of bulk brewing coffee provided 1 servings of 8 oz. • Bill of material of a typical drip coffee machine was used (European commission, 2011). Service life of the drip coffee machine is estimated at 6 years (ENERGY STAR, 2011). It was assumed that manufacturing and assembly occur in China (Quantis assumption). A sensitivity analysis on machine service life will be conducted. • Electricity consumption of a drip coffee machine includes warm-up for a temperature difference of 70°C and keep-warm mode. Measured values according to TopTen-measurements (Josephy, 2011) range from 8.1 to 14.7 Wh for 80 ml of heated water. Median value was used to model energy consumption. Keep-warm mode is reported to be 40 W on average (Nipkow, 2006). No standby mode (i.e. electronics and display are active) or off mode (i.e. the machine is inactive but is not out of tension, where residual electricity consumption usually occurs over long periods of time) were considered. Average use of the warming plate is of 37 minutes (ENERGY STAR, 2011). A sensitivity analysis on keep-warm mode duration will be performed. • A ceramic mug of 250 ml capacity (mass of 300 g) is considered to be washed after every use and is assumed to have a service life estimated at 500 use cycles. • The drip filter machine also includes a decanter that is rinsed (2 l of cold water on average) between every preparation and dish-washed every 10 preparations. The decanter is assumed to occupy 1/20 of the dishwasher. • Only mechanical dishwashing is considered for washing mugs. Lifetime, loading, detergent use and water and electricity consumption was modeled according to use phase data published by Humbert et al., 2009.

Table 6: Data and assumptions

Life cycle stage	Scenario 1: single-serve coffee	Scenario 2: Drip-brewed coffee
	washed after every use and is assumed to have a service life estimated at 500 use cycles. • Only mechanical dishwashing is considered for washing mugs. Service life, loading, detergent use and water and electricity consumption were modeled according to use phase data published by Humbert et al., 2009.	
End of life	• The service life of a single-serve capsule is of one use and was considered to be simply thrown out after brewing with the coffee waste still in it. • A landfill incineration ratio of 81:19 was used since it represents average waste management in North America (EPA, 2010). • Waste electricity was assumed to be generated by incinerated materials and displaces electricity from the average North American grid mix (Quantis internal knowledge). • Although single-serve capsules are considered to be thrown out after use, the packaging (secondary and tertiary) was considered to be recycled at a rate representing the average North American residential rate. A recycling rate of 62.5% was used to represent cardboard and corrugated packaging based on average US and Canadian rates (EPA, 2011). • The system expansion approach was used to evaluate the impacts related to the recycling of the packaging. Recycling of materials was assumed to displace virgin production but the impacts of recycling processes are accounted for in this stage. • Landfilling of coffee, paper and cardboard accounts for non-degraded carbon fraction based on reported carbon sequestration factors (Staley et al., 2009).	• The service life of a paper filter for a drip filter machine is of one use and was considered to be thrown out after brewing. • A landfill incineration ratio of 81:19 was used since it represents average waste management in North America (EPA, 2010). • Waste electricity was assumed to be generated by incinerated materials and displaces electricity from the average North-American grid mix (Quantis internal knowledge). • Filter packaging and their secondary and tertiary packaging were considered to be recycled at a rate representing the average North American residential rate. A recycling rate of 62.5% was used to represent cardboard and corrugated packaging, based on average US and Canadian rates (EPA, 2011). • For R&G coffee packaging, only the plastic lid of the can was considered to be recycled at a rate representing the average North American residential rate. A recycling rate of 8.2% for plastics was based on average US and Canadian rates (EPA, 2011). The composite can and pouch are considered non-recyclable. • The system expansion approach was used to evaluate the impacts related to the recycling of the packaging. Recycling of materials was assumed to displace virgin production but the impacts of recycling processes are accounted for in this stage. • Landfilling of coffee, paper and cardboard accounts for non-degraded carbon fraction based on reported carbon sequestration factors (Staley et al., 2009). • 3.9% of households will compost the used coffee grounds instead of throwing them out based on the average percentage of food waste that is composted in the US (EPA, 2011). Compost produced from coffee grounds was considered to displace fertilizers and peat.

Table 7: Capsule components, materials and weights
(Mother Parkers, 2012)

Description	Material	Units	Value
Abaca filter	Abaca	g	0.202
	Softwood	g	0.0224
	PE	g	0.0560
Aluminum lid	Al foil	g	0.0692
	PET	g	0.034
	PE	g	0.144
Shell	PS	g	2.52
	EVOH	g	0.0428
	PE	g	0.115
Inert gases	N2	g	0.432

Table 8: Filter packaging
(Quantis measurements and assumptions)

Description	Material	Amount of filters per format	Packaging weight (g)	% of market (Quantis assumption)
Boxed	Board box	40	26	25%
Boxed	Board box	100	30	25%
Bagged	HDPE film	100	3	25%
Bagged	HDPE film	200	5	25%

Table 9: Bulk coffee packaging
(Mother Parkers, 2014 and Quantis assumptions)

Description	Component	Material	Amount of coffee (g) per format	Component weight (g)	% of market (Quantis assumption)
Can	Lid	LLDPE	930	16	50%
	Valve	PP (Quantis assumption)		21.5	
	Peelable seal	PET/ Foil/ Nylon/ Sealant film			
	Rim	Steel			
	Body	HDPE/PET/paperboard/foil/ink		114	
	Bottom	Steel			
Pouch	Pouch	PET / ink / adhesive / foil / PE	340	14.2	50%
	Tie	Tin		1	
	Valve	PP (Quantis assumption)		1	

Additional data on the production process of abaca paper sheets, PS sheets and aluminum lids for the capsule and no. 4 filter are presented in Appendix B.

4.2.2 Data quality requirements and assessment method

Data sources are assessed on the basis of time-related coverage, geographic coverage, technological coverage, accuracy, completeness, representativeness, consistency, reproducibility, source description and uncertainty of the information as prescribed in ISO 14044. The pedigree matrix for rating inventory data is a useful tool and was used in this study as a guide to evaluate data quality and calculate uncertainty to conduct a quantitative uncertainty analysis. A complete discussion on the topic may be found in Frischknecht et al. (2007).

The importance of the data to the total system results was examined using sensitivity testing and contribution analysis. Explanations of their influence on the confidence of the results are reported in section 5.

Although every effort was made to establish the best available information and consider key influential factors such as geography, temporal relevance, scientific credibility and internal study consistency, life cycle assessment is a complex task and relies on numerous data sources and assumptions. While the results presented in this study are intended to be considered reliable, they should be used only within the context of the boundaries and limitations discussed in this report. In cases in which important information is unknown, uncertain or highly variable, sensitivity analyses were performed to evaluate the potential importance of the data gap.

4.3 Impact assessment

4.3.1 Impact assessment method and indicators

Impact assessment classifies and combines the flows of materials, energy and emissions in and out of each product system by the type of impact their use or release has on the environment. The method used here to evaluate environmental impact is the peer-reviewed and internationally recognized IMPACT 2002+ vQ2.21 life cycle impact assessment (LCIA) method (Jolliet et al. 2003, adapted by Quantis). This method assesses 17 different potential impacts categories (midpoint) and then aggregates them into four endpoint (damage) categories (Figure 4). They are presented along with the inventory indicator for water withdrawal, which is not yet accounted for in any endpoint category. The five indicators are the following:

- Climate change (in kilograms of carbon dioxide equivalents (kg CO_2 eq.));
- Human health (in disability-adjusted life years (DALYs));
- Ecosystem quality (in potentially disappeared fraction per square meter of land per year (PDF*m^2*yr));
- Resources depletion (in megajoules (MJ));
- Water withdrawal (in cubic meters (m^3)).

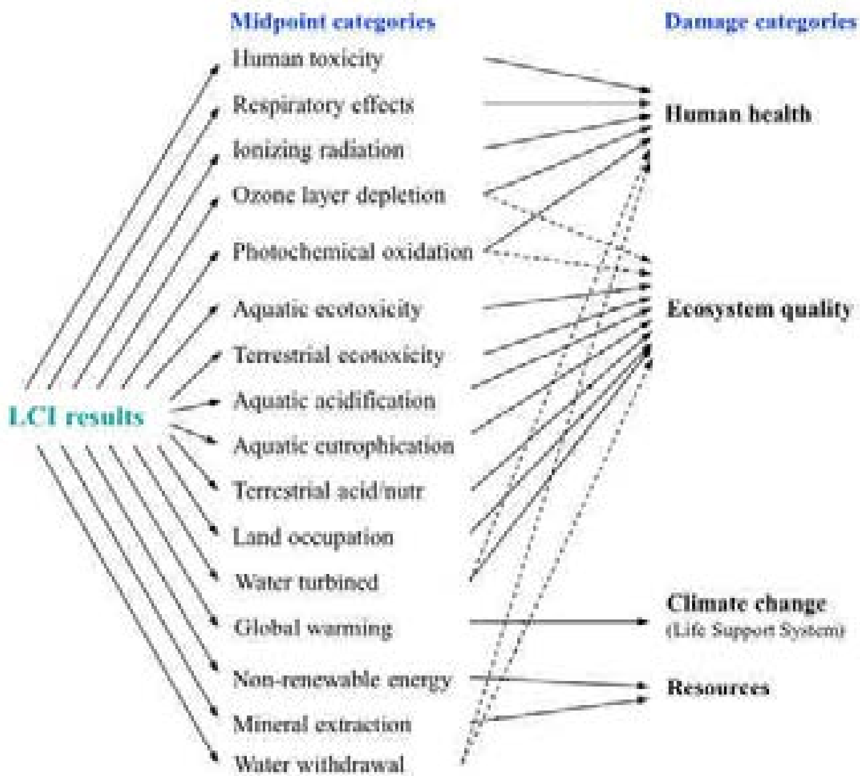

Figure 4: IMPACT 2002+ vQ2.21 midpoint and endpoint categories
(Dashes indicate links between midpoint and endpoint indicators that are currently under development)

These five main indicators were selected because they cover a comprehensive range of environmental issues without overwhelming the reader with an excessive number of indicators. Hence, this choice is believed to be an appropriate balance between the completeness of the environmental assessment and the readability and manageability of the results.

IMPACT 2002+ was updated by Quantis in order to include new trends in LCIA methodology, such as a water withdrawal indicator, to provide the greatest consistency with data that may be presented elsewhere. The exclusion of biogenic carbon dioxide and monoxide and a reduced emission factor for biogenic methane avoids a misleading combination of short cycle carbon emissions (absorbed and released by vegetation) with carbon emissions from fossil fuels, previously stored underground permanently. Detailed information on the IMPACT 2002+ vQ2.21 method and indicators is available at http://www.quantis-intl.com/pdf/IMPACT2002_UserGuide_for_vQ2.21.pdf and a description of the impact categories is provided in Appendix C.

For indicators relating to human health, only the health impacts occurring from the release of substances into the outdoor environment and human exposure in the environment are considered. Direct exposure through indoor air or dust is excluded. An indoor exposure assessment is beyond the current capabilities of life cycle science due to a lack of information on the release of chemicals from building materials and the lack of an established method to incorporate exposures within the indoor environment into a life cycle impact assessment. However, recent developments are moving toward making this feasible (Hellweg et al. 2009).

No normalization of the results was carried out, with the exception of the results presented on a relative basis (%) compared to the reference for each system. No grouping or weighting of the damage categories is done since they are presented individually and not as a single score. As stated by ISO, there is no objective method by which to achieve this.

4.3.2 Limitations of LCIA

Life cycle impact assessment results present potential and not actual environmental impacts. They are relative expressions, which are not intended to predict the final impact or risk on the natural media or whether standards or safety margins are exceeded. Additionally, these categories do not cover all the environmental impacts associated with human activities. Impacts such as noise, odours, electromagnetic fields and others are not included in this assessment. The methodological developments on these impacts do not allow for their consideration within life cycle assessment.

4.4 Calculation tool

Developed by PRé Consultants (www.pre.nl), SimaPro 7.3.3 software was used to assist the LCA modeling, link the reference flows with the LCI database and compute the complete LCI of the systems. The final LCI result was calculated combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of the two systems.

4.5 Contribution analysis

In addition to the comparative assessment, a contribution analysis was performed to determine the extent to which each modeled process contributes to the overall impact of the studied systems. Lower quality data may be suitable in the case of a process whose contribution is minimal. Similarly, processes with a great influence on the study results should be characterized by high-quality information. In this study, the contribution analysis is a simple observation of the relative importance of the different processes to the overall potential impact.

4.6 Scenarios for sensitivity analyses

The parameters, methodological choices and assumptions used when modeling the systems present a certain degree of uncertainty and variability. It is important to evaluate whether the choice of parameters, methods and assumptions significantly influences the study’s conclusions and to what extent the findings are dependent on certain sets of conditions. Following the ISO 14044 standard, a series of sensitivity analyses were used to study the influence of the uncertainty and variability of modeling assumptions and data on the results and conclusions, thereby evaluating their robustness and reliability. Sensitivity analyses help in the interpretation phase to understand the uncertainty of results and identify limitations. The following parameters and choices test the sensitivity of the results and conclusions:

- Coffee waste due to overpreparation for the drip-brewed coffee preparation (section5.1.2)
- Coffee waste due to inferior freshness retention of bulk packaging (section 5.1.3)
- Duration of the keep-warm mode for the drip-filter brewer (section5.1.4)
- Lifetime of a single-serve brewer and of a drip-filter brewer (section 5.6.1)
- Impact assessment method (section 5.6.2)

4.7 Uncertainty analysis

There are two types of uncertainty related to the LCA model:

- Inventory data uncertainty
- Characterization model uncertainty, which translates inventory into environmental impacts

4.7.1 Inventory data uncertainty analysis

A quantitative analysis of the uncertainty due to the variability of inventory data was performed. The discussion is based on the outputs of the Monte Carlo analyses conducted between compared systems with 200 to 1 000 iterations or until stabilization of variability is reached. In addition, sensitivity analyses were conducted on the most influential parameters of the model. The uncertainty factors used along with a data quality assessment are presented in Table 14.

4.7.2 Characterization model uncertainty analysis

In addition to the inventory data uncertainty described above, there are two types of uncertainty related to the LCIA method. The first pertains to the characterization of the LCI results into mid-point indicators and the second pertains to the subsequent characterization of these mid-point scores into end-point indicators. The uncertainty ranges associated with characterization factors at both levels vary from one mid-point or end-point indicator to another. The accuracy of the characterization factors depends on ongoing research in the many scientific fields behind life cycle impact modeling and on the integration of current findings within operational LCIA methods. This type of uncertainty is not yet fully understood by the LCA community. The scientific consensus on this sensitive topic and the grouping methodology is still under revision in order to better assess these ranges of uncertainty.

Quantification of inventory uncertainties using Monte Carlo is considered sufficient to draw conclusion from obtained results considering the current state of knowledge.

4.8 Coherence analysis

Coherence analysis is intended to ensure the comparativeness of the studied system. Many efforts were made to ensure coherence between models despite various data gaps. One means used to overcome the issue is to use equivalent data or models for all systems. For example, tertiary packaging for capsules is modeled from primary data provided by Mother Parkers, which was applied identically to all tertiary packaging for both studied systems. Other parts of the systems for which no primary data were available were modeled with secondary data and estimated data and are applied equivalently to all systems (e.g. life cycle stages such as distribution, use and end of life). Differences and equivalence in studied systems are specified in a dedicated section of the report.

4.9 Completeness analysis

With regards to coherence between systems, many efforts were made to ensure that models are as complete as possible. Overall, it is fair to state that the systems are nearly complete. Missing elements due to lack of data or details on specific processes include, for example, the detailed steps for the production of the abaca filter after the filter material is produced, packaging of roll stock supplies. Different levels of completion of comparison of systems or parts of systems were taken into account in discussions and considered as elements that increase the uncertainty of the results.

4.10 Critical review

This report follows ISO 14040 and ISO 14044 standards. However, it can only achieve full compliance with the ISO 14040 series standards though a critical review process. Because this study contains comparative assertions for public disclosure, a peer review process is mandatory in order to "to decrease the likelihood of misunderstanding or negative effects on external interested parties" (ISO, 2006a).

The role of the critical review, as defined in ISO 14044, is to ensure that:

- the methods used to carry out the LCA are consistent with this international standard;
- the methods used to carry out the LCA are scientifically and technically valid
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretations reflect the limitations identified and the goal of the study;
- the study report is transparent and consistent.

The critical review was carried out by a panel of independent experts. To ensure the independence of the review panel, the chairperson was selected and contracted by PAC directly. The other members of the panel where chosen by the chairperson. The panel members and their experience in relation to this study are presented in Table 10.

Table 10: Composition of the peer review panel

Member	Affiliate organization	Relevant experience
Gregory A. Norris (chairman)	Co-Director, Sustainability and Health Initiative for NetPositive Enterprise (SHINE), Harvard T.H. Chan School of Public Health	LCA practitioner since 1995, taught LCA at Harvard since 2000. Degrees in mechanical engineering, aerospace engineering, and natural resources.
Terrie Boguski (panel member)	President of Harmony Environmental	LCA practitioner since 1989. B.S. in chemical engineering, M.Sc. in environmental engineering.
Getachew Assefa (panel member)	Founder and CEO of Triple Ten Consulting	15 years' experience in LCA including teaching and research. Associate professor and Athena Chair in Life Cycle Assessment at the Faculty of Environmental Design, University of Calgary, Canada.

The critical review panel was mandated to review the final draft report of the detailed LCA study only. The detailed LCA critical review report is available in appendix E.

Note that a critical review in no way implies that the panel members endorse the results of the LCA study or the assessed products.

5 Results

The following sections present study results in the following order:

- Influence of consumer habits on results
- Global comparative results of the two studied coffee systems with varying scenarios depicting a range of consumer behaviours (as presented in Table 1)
- Contribution analyses to the climate change indicator per life cycle stage
- Summary of the key contributors to the environmental impacts of the two studied coffee systems
- Sensitivity analyses

For situations in which several indicators show a similar trend, discussion may predominantly feature the climate change impact category. In cases where other indicator results diverge from those of climate change or are otherwise important for interpretation, these differences are discussed in the report text.

As discussed in section 4.7.1, uncertainties associated with the modeled systems are quantified using Monte Carlo analysis. The results of these analyses are presented and discussed in section 5.8.

The results are presented in detail in Appendix C.

5.1 Influence of consumer habits

The parameters, methodological choices and assumptions used to model the systems present a certain degree of uncertainty and variability. This is especially the case with parameters and assumptions linked to the habits of coffee drinkers. It is important to evaluate whether the choice of consumer behaviour parameters, methods and assumptions significantly influences the study's conclusions and the extent to which the findings are dependent upon certain sets of conditions. Following the ISO 14044 standard, a series of sensitivity analyses was used to study the influence of the uncertainty and variability of modeling assumptions and data on the results and conclusions, thereby evaluating their robustness and reliability. Sensitivity analyses help in the interpretation phase to understand the uncertainty of the results and identify limitations.

To investigate the influence of consumer habits on the results, only the scenarios relevant to the studied consumer behaviour parameter were considered.

Each sensitivity analysis and its results are further detailed below. The complete results are presented in Appendix D.

5.1.1 Efficiency of single-serve brewers

There is a wide range of K-cup single-serve brewing systems on the market, and each includes a distinct set of features such as reservoirs, programming options and options to brew different cup sizes (eBay, 2014). The features that most influence the energy consumption of a single-serve brewer are the type of heater, parts insulation and heated water reservoirs (i.e. water permanently kept at 85°C to 90°C for immediate production). As for drip filter brewers, the energy consumption is mainly influenced by the time the hot-plate is in service.

Figure 5 compares the climate change impact of two types of single-serve brewers. The best case for a drip-filter brewer is also included for comparison purposes. Scenario S1a represents the best case scenario for a single-serve brewer—an energy efficient coffee machine that uses a flow type heater activated only for coffee brewing and switched off immediately when coffee production is finished (Nipkow, 2011). Scenario S1b represents the worst case scenario for a single-serve brewer, which is a brewer with a ready-to-serve mode, equipped with a reservoir of water that is kept at 85°C to 90°C for immediate production for the entire time that the mode is activated (an average of 11 hours a day was used in this study). The brewer in scenario S1b was also considered to be used in a less efficient manner with the auto-power-down feature and eco mode that reduces the temperature that the water is kept in the reservoir not being used by the consumer. As for the S2a drip-brewed coffee scenario, it represents the best case scenario for a drip-filter brewer, where no standby mode or off mode were considered and where an average use of the warming plate is of 37 minutes (ENERGY STAR, 2011). All three scenarios consider the same amount of brewed coffee.

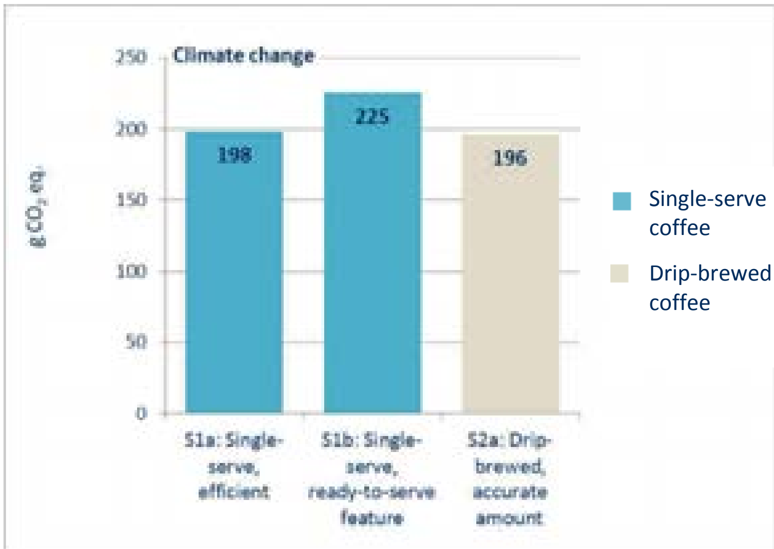

Figure 5: Climate change impact of different brewer types

The climate change score is directly influenced by the electricity consumption of the brewer. The brewers considered in S1a and in S2a both consume the same amount of electricity, which is energy to warm-up the water to a temperature difference of 70°C. Their climate change scores are therefore relatively close. As for scenario S1b, it requires a considerable amount of electricity to keep the water in the reservoir heated, which explains its higher climate change impact. Section 5.1.4 presents a more detailed comparison between single-serve and drip brewed coffee covering the brewer's energy efficiency.

5.1.2 Coffee waste due to over-preparing

Drip filter coffee preparation is done for one single cup of coffee. It could also be considered that the amount of coffee prepared is not always accurate, and to avoid the situation in which not enough coffee is prepared, the consumer tends to brew a bit more than necessary. A part of the coffee is therefore prepared in addition to the intended amount, which is referred to as waste. The additional amount of coffee prepared is considered to be, in the worst case, 50% of the intended amount (based on Humbert 2009). Figure 6 shows the influence of over preparing on the climate change impact.

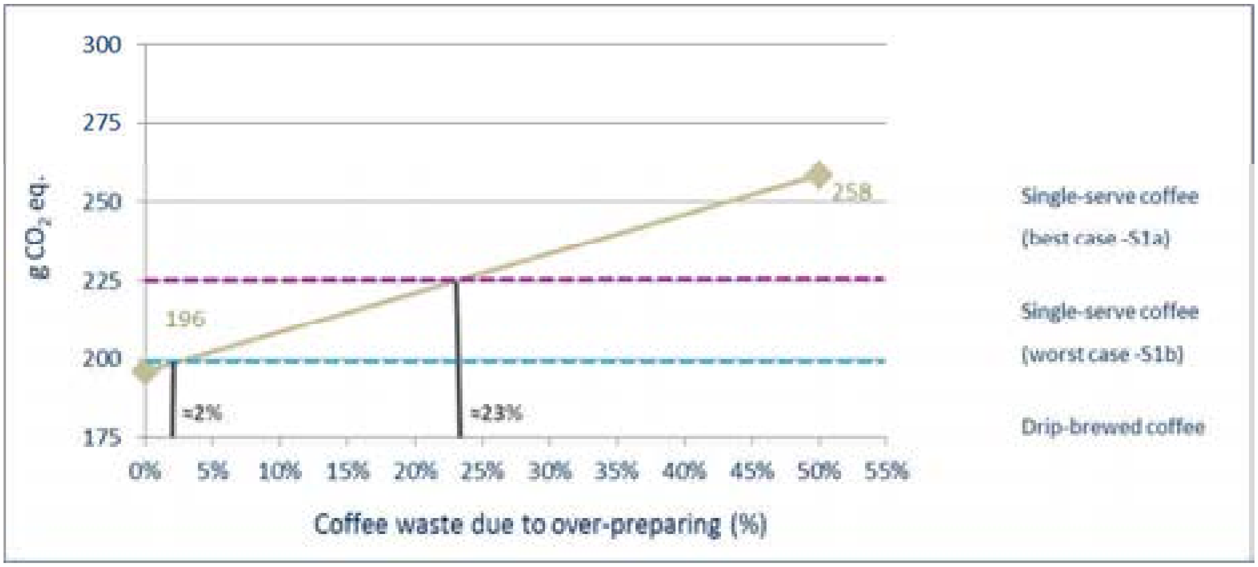

Figure 6: Climate change impact as a function of over-preparing waste

A 50% waste represents the worst case scenario whereas the best case scenario is for a perfectly dosed serving of coffee representing 0% waste. Since overpreparation implies additional coffee, the impact due to coffee supply becomes greater. Also, a consequence of overpreparation is the additional energy required to heat a larger volume of water during the brewing process. Figure 6 shows that it does not take a high waste percentage for the two systems to have an equal climate change score: with as little as 2% waste, the energy efficient single-serve coffee system appears to outperform the drip-brewed coffee system. For a non-efficient single-serve brewer, the threshold is lower than 24%.

5.1.3 Coffee waste due to inferior freshness retention

For the drip-brewed system, in addition to producing coffee waste from over-preparing, coffee waste can also occur as a result of inferior coffee packaging. Unlike single-serve capsules, which conserve their freshness up until they are inserted in the brewer, drip-brewed coffee is packaged in bulk and therefore consumed over a longer period of time, which ultimately affects the freshness of the product. Consequently, the consumer may discard a certain amount of coffee before it is consumed in its entirety. This amount of coffee is referred to as coffee waste due to inferior freshness retention. Figure 7 reports the influence of this type of waste on the climate change impact.

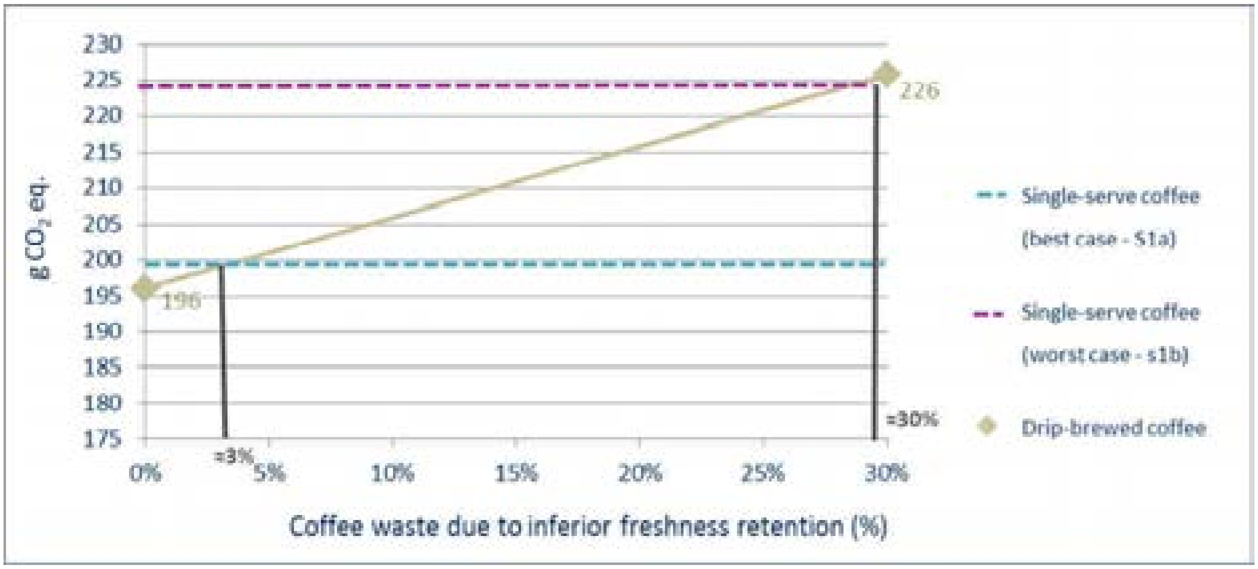

Figure 7: Climate change impact as a function of coffee waste due to inferior freshness retention

The worst case scenario considers that consumers will discard on average 30% of the bulk coffee they purchase whereas best case scenario assumes that the bulk coffee is consumed in its entirety (i.e. zero coffee waste).

In this case, the coffee waste implies additional coffee but no additional energy for preparation. As observed in Figure 7, the influence of wasting coffee as a result of inferior freshness conservation shows a trend in impact results similar to wasting coffee as a result of over-preparing: with as little as 3 % coffee waste, the energy-efficient single-serve coffee system appears to perform better than the drip-brewed coffee system. In the comparison with the non-efficient single-serve coffee system, the 30% coffee waste assumption for the worst case scenario is the tipping point between the scenarios.

Coffee waste due to over-preparing and inferior freshness retention are independent parameters that can happen concurrently at different rates. For this reason, an equation is presented in Appendix A and can be used to calculate a specific carbon footprint for a combination of the different waste rates due to over-preparing and inferior freshness retention.

5.1.4 Usage period of the keep-warm mode on a drip-filter brewer

Although the drip-filter brewer does not hold heated water for a ready-to-serve mode, it does possess a hot plate for the keep-warm mode. The average use of the warming plate is 37 minutes (ENERGY STAR, 2011) and is considered to be the best case scenario. The worst case scenario will consider a longer use of the warming plate of about 2 hours. The influence of the keep-warm period on climate change is reported in Figure 8.

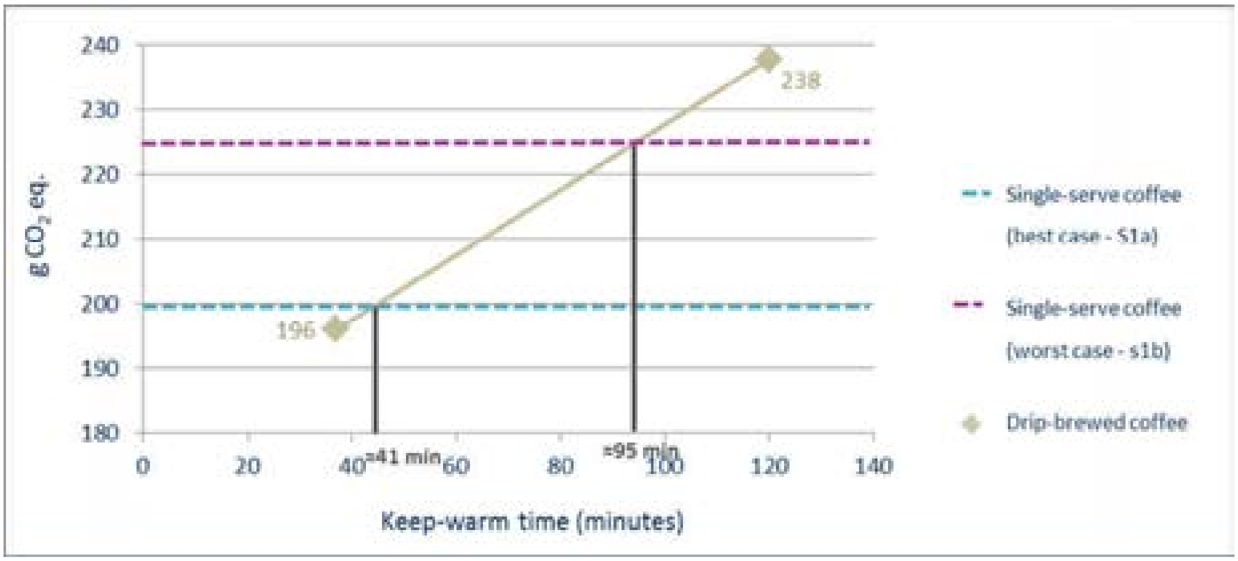

Figure 8: Climate change impact as a function of keep-warm duration

The climate change score for the best case scenario for the single-serve coffee system (S1a at 196 g of CO_2 eq.) is very close to that of the best case scenario for the drip-brewed coffee system (S2a at 198 g of CO_2 eq.). However, the single-serve coffee system presents a better environmental performance than the drip-brewed coffee system as soon as the keep-warm time goes over 41 minutes, and the impact score gap between these two scenarios becomes more predominant as the keep-warm time increases. Figure 8 also shows that the worst case scenario for the single-serve coffee system (S1a at 225 g of CO_2 eq.) has a better environmental performance as compared to the drip-brewed coffee system when the hot-plate is in operation for more than 95 minutes.

5.2 Overall comparative results

In this section, the overall comparative results of the two studied coffee systems for the varying scenarios (see Table 1) are presented.

5.2.1 Climate change

The complete life cycle results for the two coffee systems and their scenarios are presented in Figure 9 for the climate change impact indicator.

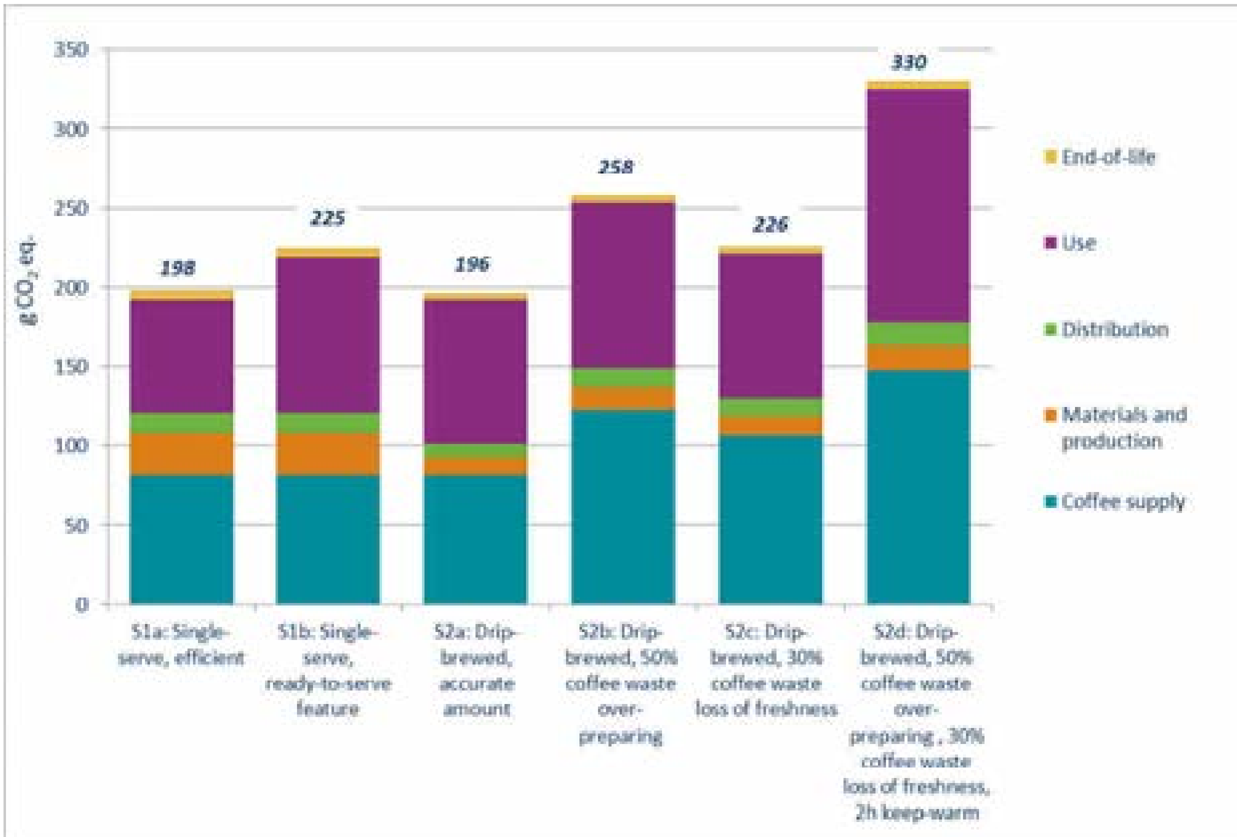

Figure 9: Overall comparative results for climate change

First, in all systems studied and for all impact indicators, the most important contributors to the full life cycle impact are the coffee supply and use stages, followed by the materials and production stage. The distribution stage represents 7% or less of the overall impact for all scenarios and indicators, while the end-of-life stage for both studied coffee systems does not significantly contribute to the overall life cycle impact (no more than 3% for all impact indicators and all scenarios).

When compared, the best case scenarios for both coffee system (S1a and S2a) are considered environmentally equivalent. However, when the single-serve coffee system considers a brewer that conserves an amount of hot water for immediate preparation (S1b), it is outperformed by the best case scenario for the drip-brewed coffee system (S2a). On the other hand, it is important to bear in mind that the best case scenario (S2a) for the drip-brewed coffee system is not representative of the average consumer behaviour, since, in the case of bulk brewing, the amount of coffee prepared is not always accurate and to avoid a coffee shortage, the consumer tends to prepare a bit more than necessary. When a more realistic scenario is considered for the drip-brewed coffee system including coffee waste, whether it be waste generated as a result of over-preparing (S2b) or inferior packaging freshness retention (S2c), the single-serve best case scenario will present a better environmental performance. As presented in sections 5.1.2 and 5.1.3, it takes only 2% coffee waste due to over-preparing and approximately 3% coffee waste due to inferior freshness retention pushed the climate change score for the drip-brewed system higher than the score for the single-serve best case scenario.. When compared to the less efficient single-serve coffee machine (ready-to-serve mode, S1b), the tipping points for coffee waste due to overconsumption and inferior freshness retention are 23% and 30%, respectively. And when both types of coffee waste are considered in the same scenario (S2d), the impact score disparity between the two studied coffee systems becomes even wider.

The scenario comparisons for the human health, resources and water withdrawal indicators follow suit with the results and discussion presented for the climate change impact. For this reason, they are not discussed in this section but rather presented in Appendix D.

An uncertainty assessment for all indicators is available in section 5.8. This assessment confirms the conclusions presented above and in the next section (5.2.2). The system differences highlighted in the text are deemed significant. In other words, there is no to very little probability (less than 15%) of reversing these conclusions due to the uncertainty of the underlying data.

5.2.2 Ecosystem quality

The complete life cycle results for the two coffee systems and their scenarios are presented Figure 10 for the ecosystem quality impact indicator.

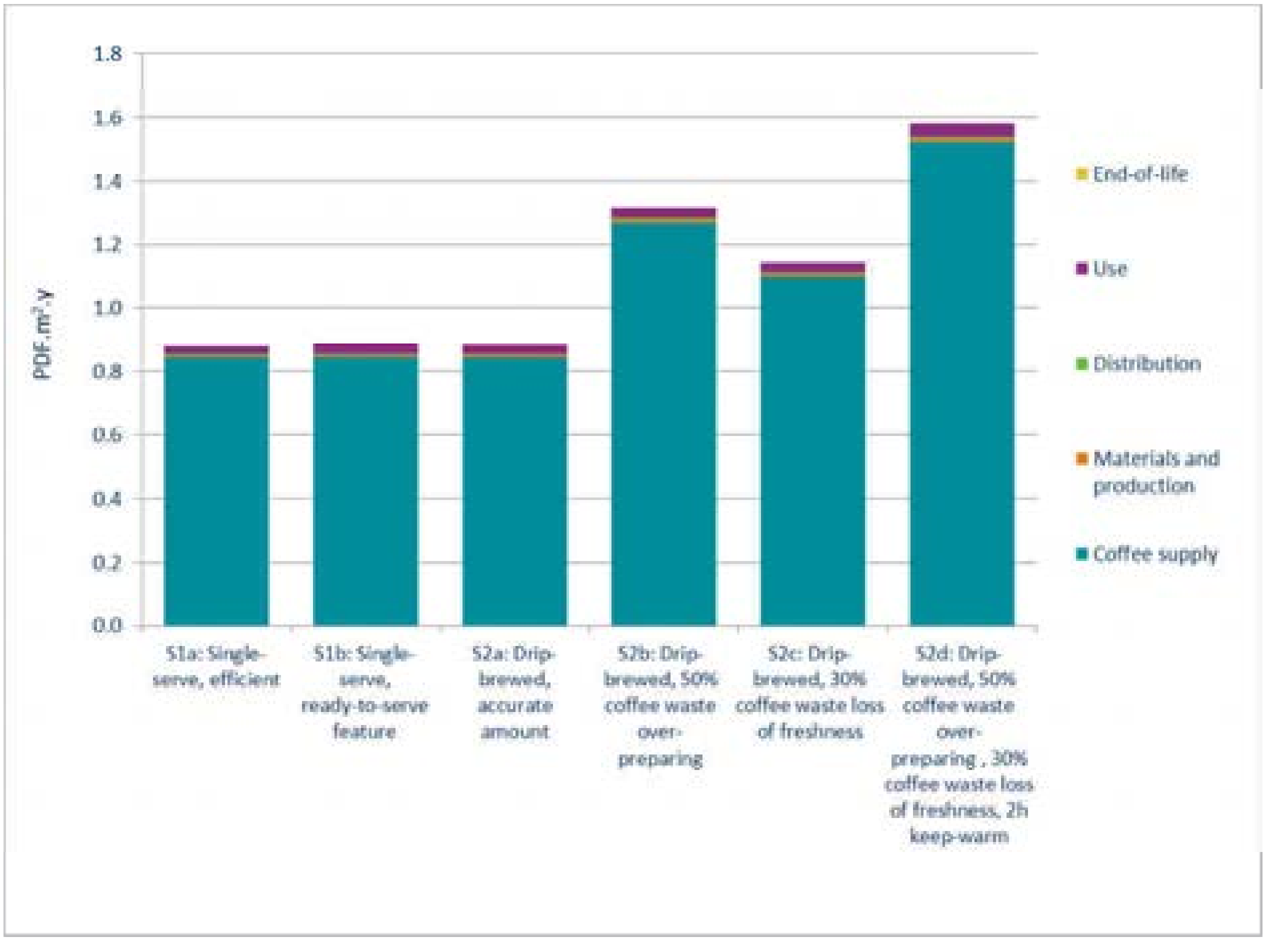

Figure 10: Overall comparative results for ecosystem quality

The ecosystem quality impact throughout the life cycle of a serving of coffee is mainly attributed to coffee supply, with a contribution of 96% or more to the overall impact. More specifically, the impact is driven by land use for coffee cultivation. For this reason, differences in energy consumptions between scenarios do not amount to differences in ecosystem quality impact scores. The scenarios with the lowest ecosystem quality scores (S1a, S1b and S2a) are the ones that do not produce any coffee waste and therefore minimize coffee supply.

5.2.3 Water withdrawal

The complete life cycle results for the two coffee systems and their scenarios are presented in Figure 11 for the water withdrawal inventory indicator.

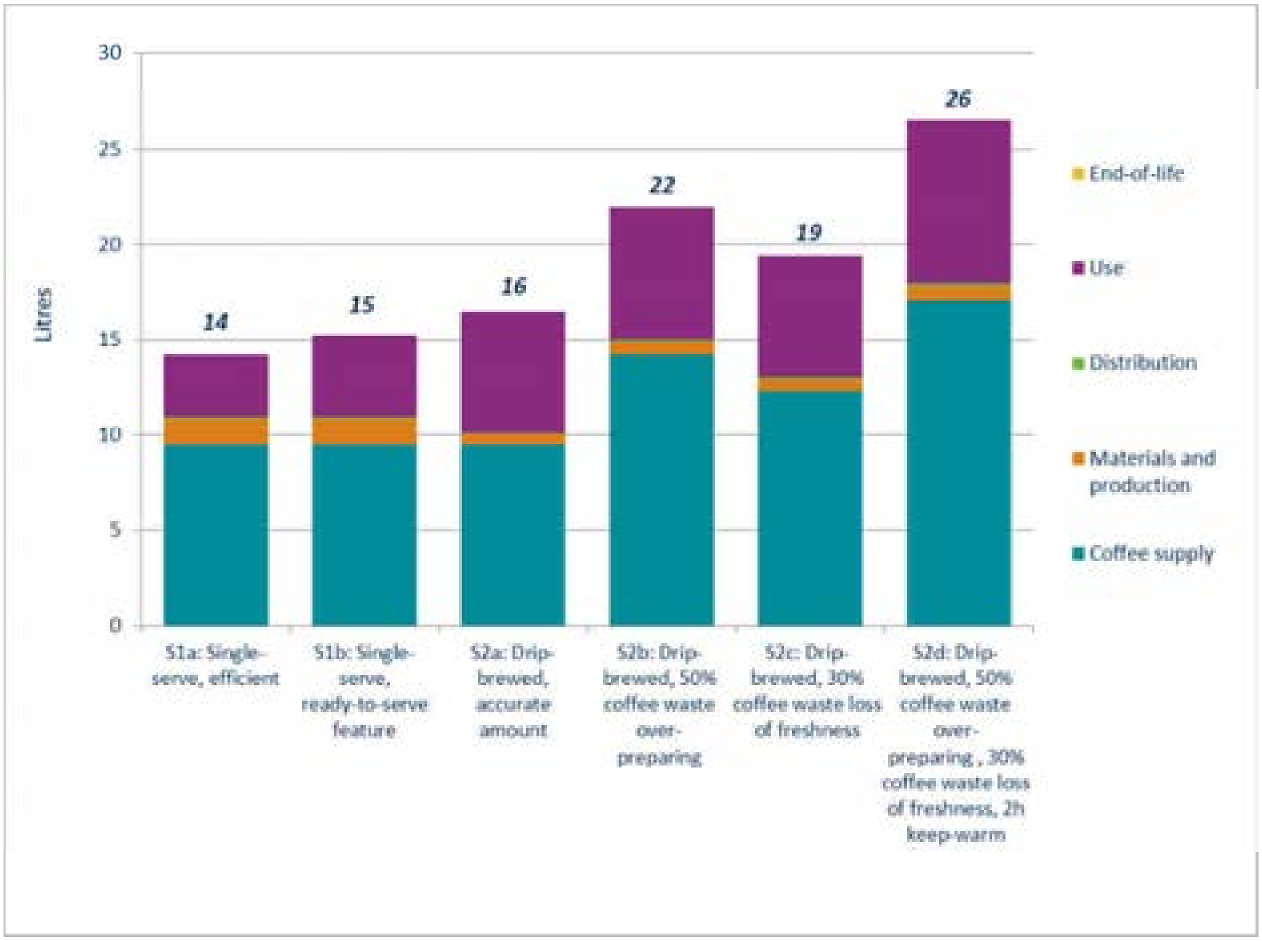

Figure 11: Overall comparative results for water withdrawal

To a lesser extent than for the ecosystem quality indicator, coffee supply is the main contributor to the water withdrawal inventory indicator. Most of the water use is for green bean washing. The second most important contributor is the use stage. In this case, water is used for coffee preparation, dishwashing and rinsing and for the production of the electricity consumed by the coffee brewer and the dishwasher. The additional requirement of water for rinsing or dishwashing the decanter and coffee overpreparation explain why the drip-filter systems do not perform as well when compared with the results for the climate change score (see Figure 9). Interestingly, although the difference is small between the best case scenarios for both coffee systems (S1a and S2a), the uncertainty assessment shows that the single-serve system performs significantly better than the drip-filter (see Figure 19).

5.3 Inventory flow contribution analysis

The damage and inventory indicators presented or discussed in the previous section are obtained through the aggregation and summation of several hundred environmental flows, mainly emissions to air, water and soil or resources taken from nature. This section aims to provide an overview of the key environmental flows contributing to each damage or inventory indicator considered in the study. Table 11 presents a list of the main flows that contribute to at least 5% of each of the five main indicators in this study. Since there are significant similarities between the different scenarios, they all share approximately the same list of inventory flows. Thus, it is rather the absolute amount of these flows that defines the relative environmental performance between scenarios. A complete list of inventory flows is available in Appendix D.

Table 11: Main inventory flows in this study

Damage or inventory indicator	Environmental flows	Sources
Climate change	Carbon dioxide	Combustion of fossil fuel for electricity production and transport Land use change for coffee cultivation
	Nitrous oxide	Fertilizer use for coffee production
	Methane	Biomass decomposition in landfill (e.g. coffee)
Human health	Nitrogen oxides	Combustion of fossil fuel for electricity production (coal) and transport
	Particulates (2.5 µm)	
	Sulfur dioxide	
Ecosystem quality	Loss of biodiversity due to deforestation	Specific characterization factor used to capture the impact of deforestation
	Copper in soil	Fertilizer use for coffee production
	Land occupation	Land use for coffee cultivation
Resources	Crude oil	Production of diesel for transportation activities and production of plastic materials
	Natural gas	Heat and electricity production
	Coal	Electricity production
	Uranium	
Water withdrawal	Fresh water	Green bean washing Tap water
	Cooling water	Electricity production

5.4 Climate change contribution analysis per life cycle stage

This section looks into the main contributors to the impact of the two studied coffee systems per life cycle stage and takes a closer look at what causes the difference in impact within each life cycle stage.

Since most of the impact indicators show a similar trend, the results and discussion feature the climate change impact category. In cases in which other indicator results diverge from those for climate change or are otherwise important for interpretation, the differences are discussed in the report.

It should be noted that not all scenarios described in Table 1 are considered to investigate impact contributions. Only the ones relevant to key contribution identification and interpretation for the life cycle stage being assessed were taken into account.

5.4.1 Climate change contribution for the coffee supply stage

The coffee supply stage includes the production and transport of R&G coffee.

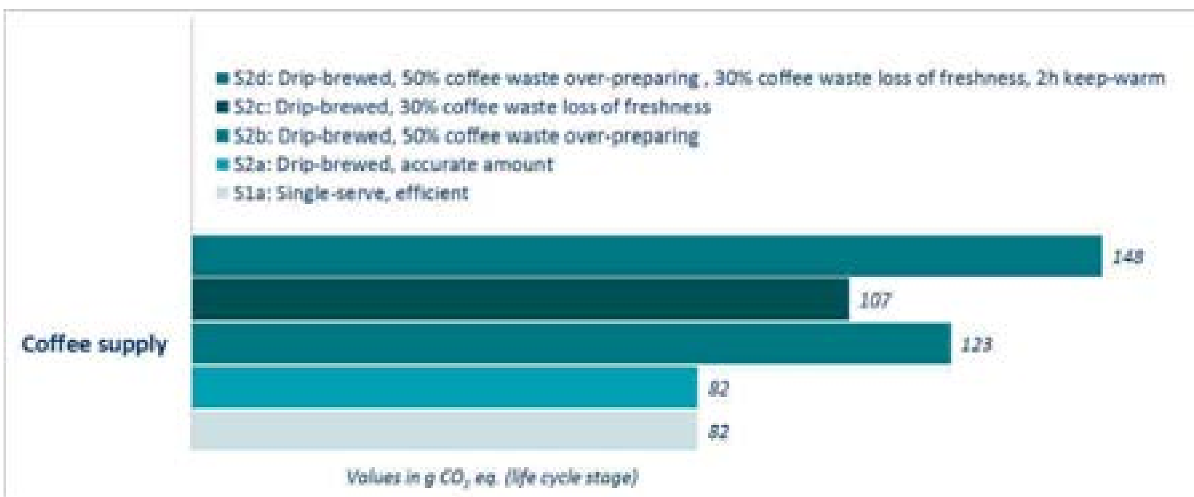

Figure 12: Climate change contribution (in g CO_2 eq.) for the coffee supply stage

The impact is mostly driven by green coffee bean procurement, mainly because of cultivation and irrigation.

The amount of coffee required to prepare one serving is considered equivalent in the single-serve and drip-brewed best case scenarios (S1a and S2a). When coffee waste come into play, whether it be waste generated as a result of overpreparation (S2b), inferior packaging freshness retention (S2c) or both (S2d), the single-serve best case scenario will have a better environmental performance.

5.4.2 Climate change contribution for the materials and production stage

The materials and production stage includes the transport and production of the systems' components (capsule and filter) and their packaging as well as bulk R&G coffee packaging (primary, secondary and tertiary). Figure 13 presents the contributions of the system components and packaging to the materials and production stage. Each component and packaging element presented in Figure 13 includes the production of the raw materials that constitute it and transport.

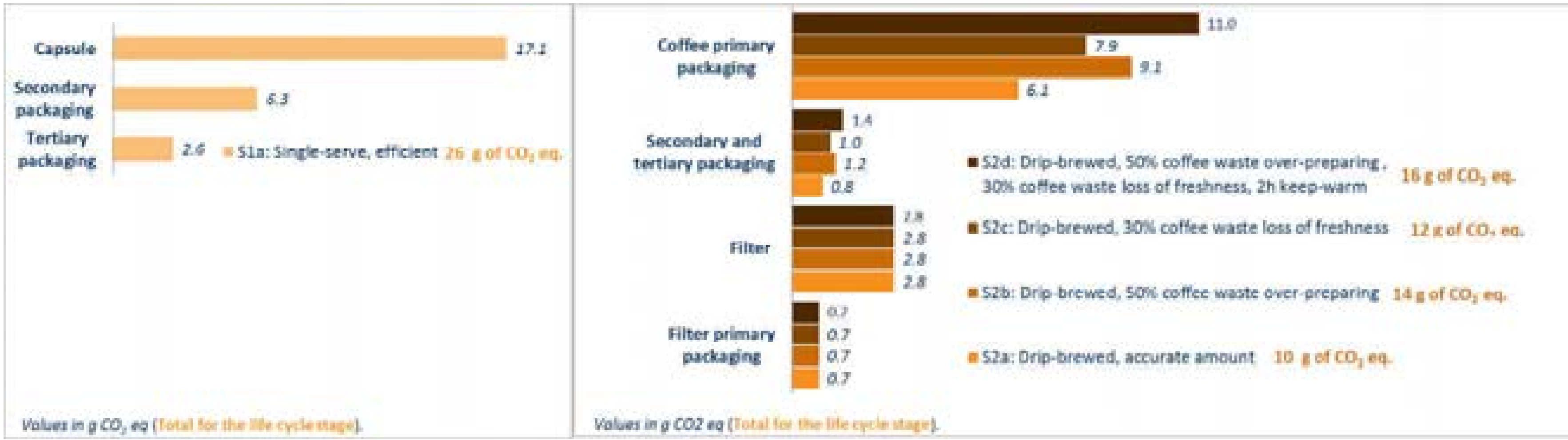

Figure 13: Climate change contribution (in g CO_2 eq.) for the materials and production stage

For the single-serve coffee scenarios, the packaging system including the capsule mainly contributes to the impact because of the significant amount of manufactured material per cup of coffee (65% of the climate change impact for the materials and production stage). As for the drip-brewed coffee scenarios, the bulk coffee primary packaging and, more specifically, the composite can contribute to the impact.

The materials and production impact is lower for the drip-brewed coffee scenarios (S2a, S2b, S2c and S2d) than for the best case single-serve coffee scenario (S1a) for the climate change impact and other impact categories and has a lesser contribution due to its lighter packaging and lack of capsule. The additional amount of coffee required due to coffee waste (S2b, S2c and S2d) only slightly increases the impact of the material and production stage since a marginally larger fraction of R&G packaging is required for the coffee surplus.

5.4.3 Climate change contribution for the distribution stage

Distribution includes all transport related to the capsules, filters and bulk coffee from the manufacturing plant to the distribution centre and then to the retailer. The distance and mode scenarios were kept equivalent between systems. However, since the different packaging systems vary in weight, the impact of their transport is not equivalent.

Figure 14: Climate change contribution (in g CO_2 eq.) for the distribution stage

The transport of the system components, coffee and packaging contributes to over 99% of the distribution stage impact. Warehousing and shelving impacts were considered negligible.

The drip-brewed coffee scenarios (S2a, S2b and S2c) show slightly lower or equal environmental burdens for the distribution stage as compared to the single-serve scenario (S1a) for the climate change impact and other impact categories. This may be explained by the lighter packaging and lack of capsule (only requires a fraction of distribution packaging). However, as the amount of coffee waste increases, the additional amount of distributed coffee cancels this advantage.

5.4.4 Climate change contribution for the use stage

The use stage includes the energy required for coffee preparation (water heating for a temperature difference of 70°C) for the single-serve brewer and the drip filter coffee machine. The energy use of the hot plate is also considered for the drip filter coffee machine. Also included in this stage for both scenarios is the manufacturing of the coffee brewer, coffee mug and dishwasher and the washing of the mug in the dishwasher. For the drip-brewed coffee system, the rinsing and dishwashing of the decanter was also considered. Figure 15 presents the contributions for the use stage. Coffee preparation includes the electricity requirements for all types of brewers, whether it is to keep water hot for immediate preparation (ready-to-serve mode), heat the water (brewing) or use the warming plate (keep-warm mode).

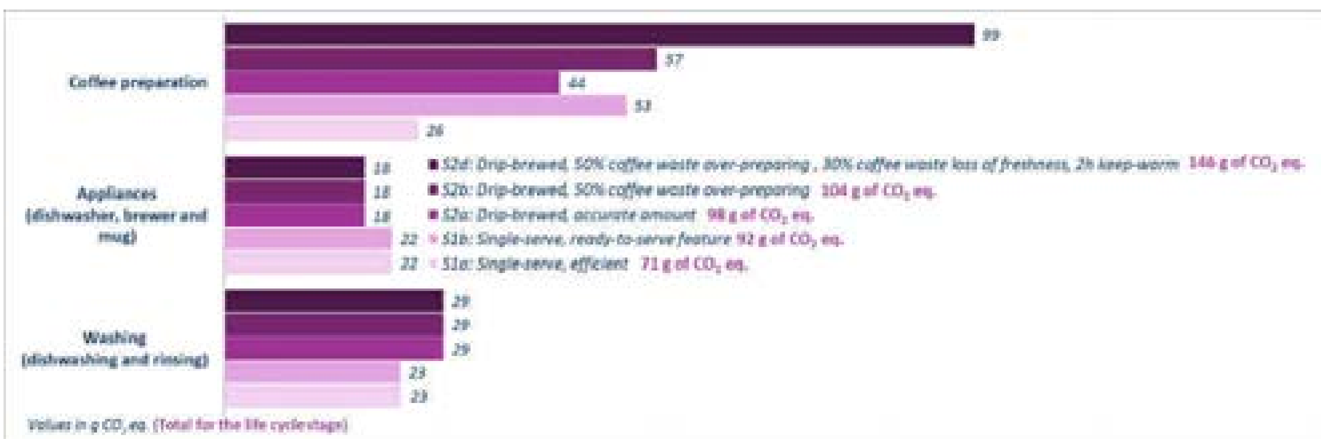

Figure 15: Climate change contribution (in g CO_2 eq.) for the use stage

The results indicate that the use of the brewers in coffee preparation has an important impact contribution ranging from 36 (single-serve –S1a) to 68% (drip-brewed – S2d) of the use stage climate change impact or 13 to 30% of the climate change impact over the entire life cycle of the coffee systems. The dishwashing and rinsing of the mugs and decanter are also important contributors because of energy-intensive washing by home dishwashers. For the efficient single-serve brewer, the climate change impact contribution reaches 33% of the use stage or 12% of the total life cycle. For the drip-brewed worst case (S2d), the same contribution to the use stage is 20% or 9% of the entire life cycle.

It is important to note that there is significant variability in the way people wash their crockery and in the efficiency of dishwashers, and the difference between the single-serve and drip-brewed systems depends on these parameters. Because drip-brewed scenarios generate slightly more dirty dishes, the difference between the scenarios would unlikely be reversed by a change in these parameters.

Brewer manufacturing for the single-serve and drip-filter represents respectively between 20 and 31% or 13 to 22% of the use stage climate change impact, which represents only around 6 to 11% of the climate change impact over the entire life cycle of the coffee systems. Single-serve brewer manufacturing is more impactful for the single-serve brewer because the machine itself has a 22% higher carbon footprint and, according to a national US consumer survey (ENERGY STAR, 2011), their usage frequency is 19% lower than for drip-filter brewers.

The differences in impact score between the scenarios are due to varying electricity consumption depending on brewer type, water volume to heat and coffee warming duration. Energy consumption for coffee preparation in the studied scenarios is presented in Table 12. The scenario that considers additional coffee to make up for waste from inadequate freshness retention by packaging (S2c) is not presented here since its use stage energy consumption is not affected by the coffee waste: no additional water is heated as opposed to the waste due to overpreparation (S2b).

Table 12: Energy consumption by scenario according to different brewer modes

Scenario	Energy consumption (Wh)			
	Ready-to-serve	Brewing	Keep-warm	**Total**
S1a	0	34	0	**34**
S1b	36	34	0	**70**
S2a	0	34	25	**59**
S2b	0	51	25	**76**
S2d	0	51	80	**131**

Overall, the best case scenario for the single-serve brewer using a flow-type heater (S1a) is less energy intensive since it only requires electricity for water heating. However, when considering a single-serve brewer that is equipped with a reservoir to permanently keep water hot for the ready-to-serve mode (S1b), the best case scenario for the drip-filter brewer becomes a more energy efficient option.

The drip-filter brewer scenarios with a 50% overpreparation waste (S2b and S2d) require additional energy to heat a larger volume of water, and the drip-filter brewer that also considers a longer coffee warming period (S2d) draws additional electricity since the keep-warm mode is activated for a longer period.

5.4.5 Climate change contribution for the end-of-life stage

The end-of-life stage addresses activities associated with the waste management of the coffee, filter, capsule and packaging.

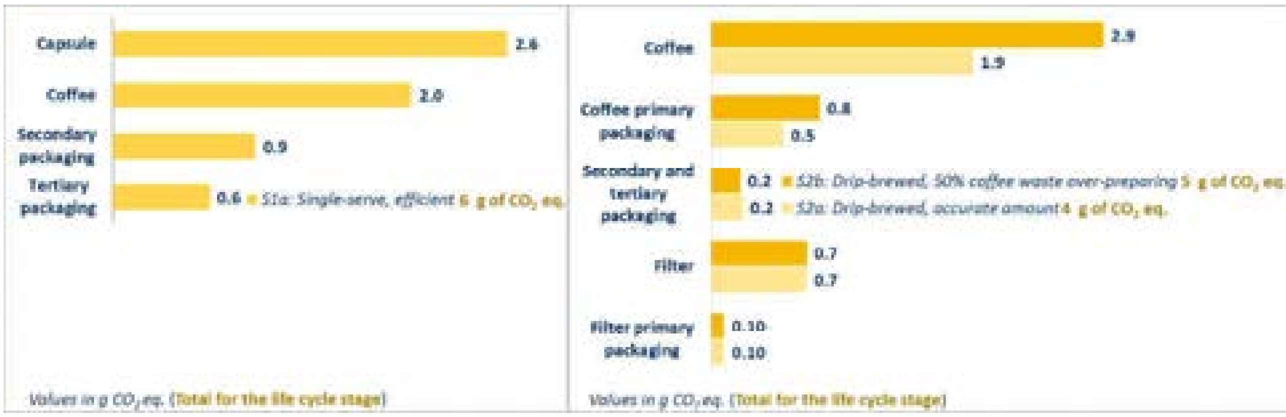

Figure 16: Climate change contribution (in g CO_2 eq.) for the end-of-life stage

The end-of-life stage in the studied coffee systems does not significantly contribute to the overall life cycle impact (no more than 3% for all impact indicators and all scenarios).

The end-of-life impacts are mainly due to the transport of the coffee and packaging waste to the waste treatment centres. The amount of packaging waste to transport and manage (recycling, incineration or landfilling) is slightly greater for the single-serve scenario.

5.5 Summary of key contributors

This section highlights the key contributors to the environmental impact of the two studied coffee systems per life cycle stage.

For the single-serve and drip-brewed systems, the **coffee supply stage** impact is driven by green coffee bean procurement, mainly because of cultivation and irrigation.

The **materials and production stage** impact for the single-serve coffee system is mostly attributable to the packaging system, including the capsule, because of the large amount of manufactured material per cup of coffee. As for the drip-brewed coffee system, the bulk coffee primary packaging and, more specifically, the composite can are responsible for most of the materials and production stage impact.

For both coffee systems, product transport is responsible for more than 99% of the **distribution** stage impact for all impact indicators.

The contribution to the **use stage** impact of both coffee systems is mainly due to the use of the brewer and the dishwashing of the mug because of energy-intensive washing in home dishwashers.

The **end-of-life** impacts are chiefly due to the transport of the coffee and packaging waste to the waste treatment centres.

5.6 Sensitivity analyses

Sensitivity analyses related consumer behaviours were discussed and presented along with the results in section 5.1.

Additional analyses are presented in this section to complete the evaluation of the variability and uncertainty of the model. The following parameters and choices were varied to test the sensitivity of the results:

- Service life of a single-serve brewer and a drip-filter brewer
- Impact assessment with the ReCiPe method

Each sensitivity analysis and its results are further detailed below. The complete results are presented in Appendix D.

5.6.1 Service life of a single-serve brewer and a drip-filter brewer

Another parameter that was investigated through sensitivity analysis is the service life of the single-serve and drip-filter brewers. The contribution analysis presented in Figure 15 showed that up to 31% of the use stage climate change impacts are attributed to the brewer's production. Furthermore, the selected service lives of 7 years for the single-serve brewer and of 6 years for the drip-filter brewer are conservative as compared to the actual service lives of such appliances according to discussion forums and blogs (e.g. The Coffee Spill, 2014 and Auromacup, 2014). The blog The Coffee Spills (2014) estimates the service lives of Keurig brewers to range between 9 to 12 months. Figure 17 presents overall life cycle climate change impact for both systems brewers for services lives of 5 years less and 5 years more than the baseline service lives.

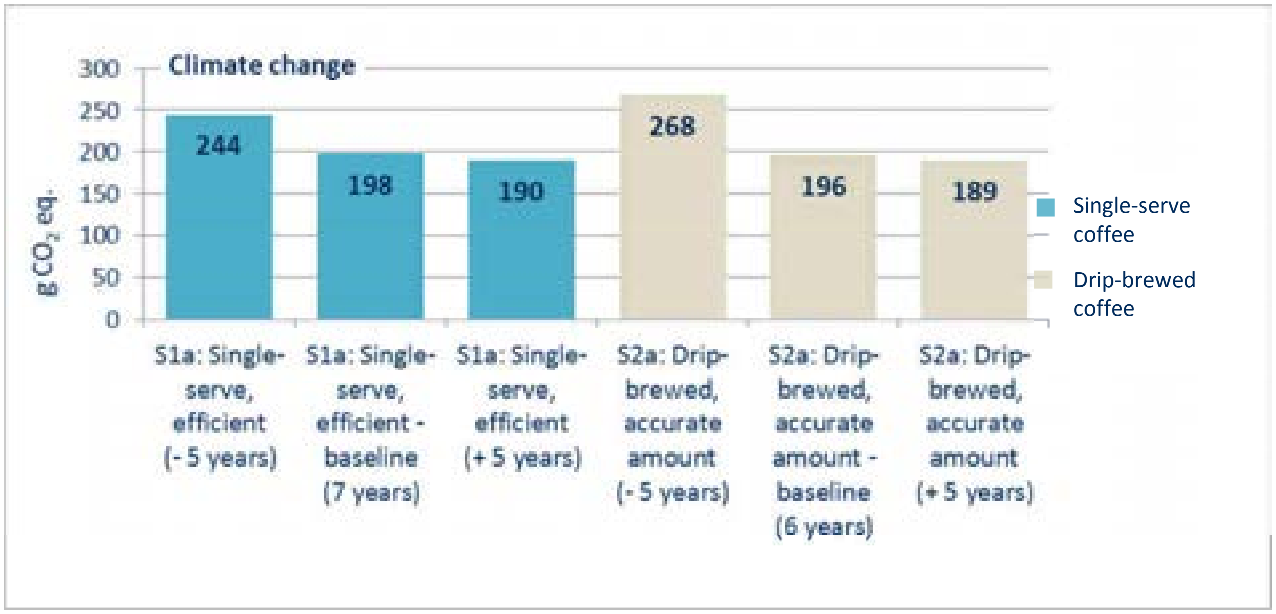

Figure 17: Climate change impact for different brewer service lives

Figure 17 shows that both types of brewers with a service life of 5 years less become important contributors to the overall life cycle impacts. The increased impacts could offset the gains from the development of an energy-saving brewer. Thus, it is essential to consider the energy-saving capabilities and service lives of the brewers.

5.6.2 Impact assessment with the ReCiPe method

The IMPACT 2002+ LCIA method is used in this study. The methodology is recognized by the LCA community (Jolliet, 2003). However, other methodologies are known, recognized and may be used in LCA studies. ISO recommends comparing LCA results with the results obtained with a different LCIA methodology to confirm that the trends and conclusions are not depend on impact assessment methodologies. In other words, it is an additional crosscheck that makes it possible to consider the uncertainty linked to impact assessment. The results obtained with the ReCiPe (Goedkoop 2009) and Impact 2002+ LCIA methods are presented in Figure 18.

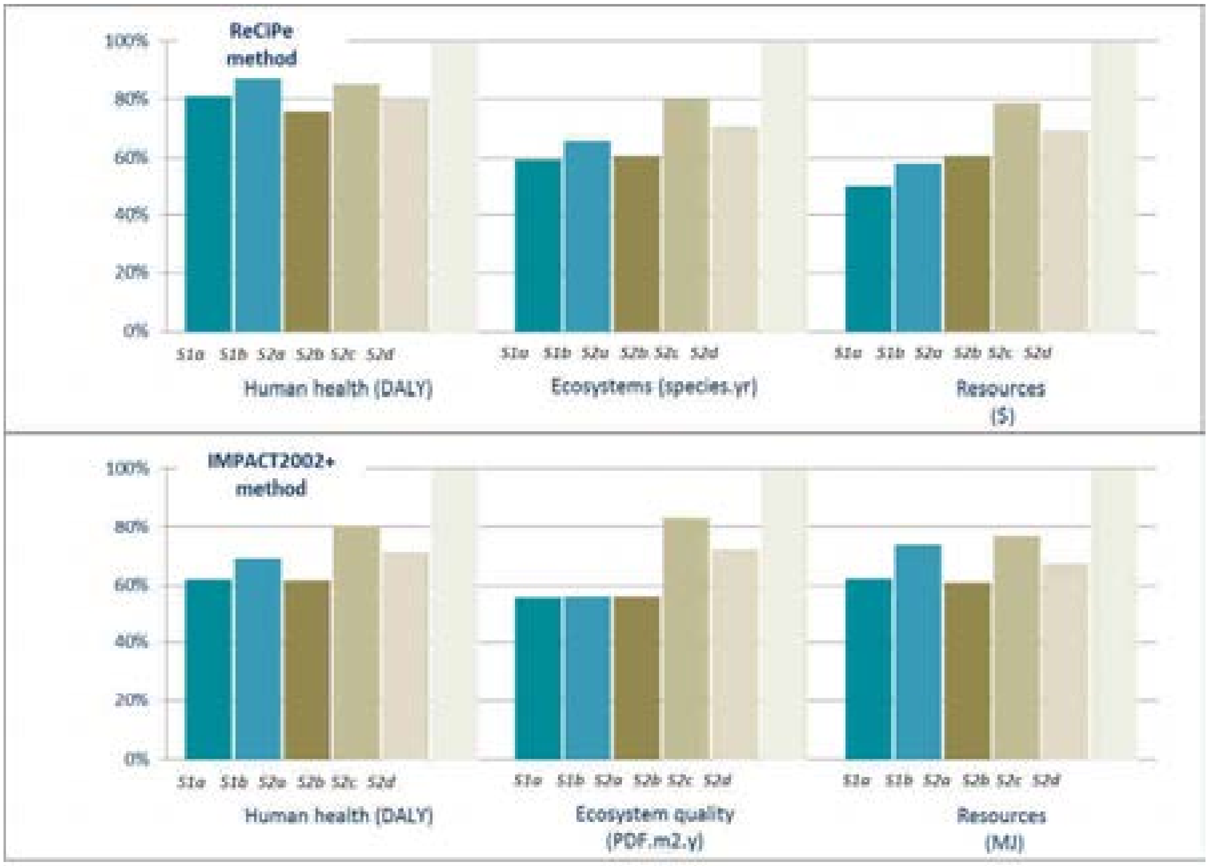

Figure 18: Life cycle impacts according to two different LCIA methods

A sensitivity analysis of the LCIA methodologies shows that the findings and trends seem independent of the impact assessment method for the human health indicator.

Contrary to the IMPACT2002+ impact assessment method, ReCiPe incorporates climate change effects into the human health and ecosystems indicators. For this reason, the trend is not exactly the same between the two methodologies for the ecosystem indicator. With IMPACT2002+, most of the ecosystem quality impact is driven by land use for coffee cultivation, whereas, with ReCiPe, the impact is also affected by climate change. Differences between scenarios in brewer energy consumption therefore come into play.

However, for the resources indicator, the ranking of scenarios S1b and S2a is reversed since the importance of metals and non-renewable resources to the resource impact indicator varies between the two impact assessment methods. In fact, ReCiPe assigns greater weight to metal depletion than IMPACT2002+. Conversely, IMPACTS2002+ attributes greater importance to non-renewable resources than ReCiPe. Hence, the impact associated with metals is more signficant when using the ReCiPe method. In fact, this is the case for the metal tin that makes up the tie of the bulk R&G coffee pouch in system 2. Tin has the highest metal depletion characterization in both methods, and its impact on resources (and mainly on metal depletion) become more significant when considering a different impact assessment method.

5.7 Inventory data quality assessment

A qualitative analysis of the uncertainty due to the variability of the inventory data was carried out for data and groups of data. Indications on the quality of data include the evaluation of the reliability and completeness of the data itself combined with the evaluation of the representativeness (temporal, geographical and technological) of the processes used to model it. The significance of the data quality scores is presented in Table 13. The data quality evaluation is presented in Table 14.

The discussion is based on the outputs of the sensitivity analyses conducted on the most influential model parameters. It considers the results of the data quality assessment and the level of correlation between the data used in the compared systems.

The importance of the data to the life cycle impacts was also evaluated based on a contribution analysis and sensitivity analyses.

Table 13: Pedigree matrix used for data quality assessment derived from Weidema and Wesnaes (1996)

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites over adequate periods	Representative data from an adequate number of sites over shorter periods	Representative data from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or over shorter periods
Temporal correlation	Less than 3 years' difference to year of study	Less than 6 years' difference	Less than 10 years' difference	Less than 15 years' difference	Age of data unknown or more than 15 years' difference
Geographic correlation	Data from study area	Average data from larger area that includes the studied area	Data from areas with similar production conditions	Data from areas with slightly similar production conditions	Data from unknown areas or areas with very different production conditions
Further technological correlation	Data from studied businesses, processes and materials	Data from studied processes and materials from different businesses	Data on studied processes and materials from a different technology	Data on related processes or materials with the same technology	Data on related processes or materials with different technology

Table 14: Data quality evaluation and importance of data contribution to life cycle impacts

Data	Source	Importance	Indicator score (see Table 13 for interpretation)				
			Reliability	Completeness	Temporal correlation	Geographic correlation	Further technological correlation
Coffee supply stage							
Coffee production	2		2	1	1	1	2
Materials and production stage							
Capsule components and production	1, 2		1	3	1	3	2
Capsule 2nd and 3rd packaging	1, 2		1	1	1	1	1
Bulk coffee primary, 2nd and 3rd packaging	1, 2		2	5	1	1	2
Drip filter	2		2	5	1	1	2
Drip filter primary, 2nd and 3rd packaging	2		2	5	1	1	2
Distribution stage							
Transport	2		5	5	5	5	5
Warehousing	2		2	5	2	2	4
Retail shelving	2		2	5	2	2	4
Use stage							
Mug production and end of life	2		3	5	2	3	2
Dishwasher production, use and end of life	2		3	5	2	3	2
Brewer production and end of life	2		2	5	1	3	3

Table 14: Data quality evaluation and importance of data contribution to life cycle impacts

Data	Source	Importance	Indicator score (see Table 13 for interpretation)				
			Reliability	Completeness	Temporal correlation	Geographic correlation	Further technological correlation
Brewer energy consumption	2	[red]	2	2	1	1	2
End-of-life stage							
Coffee	2	[green]	2	5	3	3	3
Capsule	2	[green]	2	5	3	3	3
Coffee primary packaging	2	[green]	2	5	3	3	3
Filter	2	[green]	2	5	3	3	3
Filter primary packaging	2	[green]	2	5	3	3	3
2nd and 3rd packaging	2	[green]	2	5	3	3	3

Data source

1 Primary
2 Secondary
0 None

Importance

[red] High
[orange] Moderate
[green] Low

The analysis shows that, overall, the quality of the data used for the modelling is considered to be good. Coffee production, shown to be a key contributor and important element to a consumer behaviour that is prone to producing coffee waste, was modelled in a strong, ISO-compliant LCA study (Coltro, 2006). Similarly, brewer energy consumption, also shown to be a sensitive parameter, was taken from TopTen published product review papers. TopTen is a consumer-oriented online search tool that is rigorous, transparent (with an extensive selection methodology) and independent from manufacturers and commercial distributors. TopTen relies on neutral tests and analyses by independent institutions, labels and standardized manufacturer declarations. The contribution of the dishwashing also proved to be important to the use stage impacts but the data quality turned out to be relatively low. However, this does not influence the overall comparison since dishwashing is not a differentiating element between the two coffee systems.

It can therefore be stated that data quality is robust.

Sensitivity and data quality analyses also showed that brewer service lives were sensitive data. Thus, refining the data on brewer service lives for both systems would lead to better and more accurate comparative profiles of single-serve versus drip-brewed coffee.

5.8 Uncertainty assessment

Inventory data uncertainty can sometimes be a key interpretive element in LCA. However, in the current study, the compared systems are highly correlated since coffee production, distribution profiles and packaging production methods are all modelled using similar data and the same process for the same database. Many materials are alike in the systems, and the distribution profiles are identical.

An analysis of the uncertainty due to the variability of inventory data was carried out. The SimaPro 7.3.3 software includes a module for Monte Carlo simulations, which enables the assessment of the variability embedded in the inventory data spread over final results. The results then become probabilistic. The analysis was conducted for 200 to 1 000 iteration steps or until the stabilization of the variability with a confidence interval of 95%.

The results are presented for the comparison between the best and worst case scenarios. Figure 19 presents the results of the Monte Carlo simulation for the comparison of:

1. Single-serve coffee system best case scenario (S1a) and drip-brewed coffee system best case scenario (S2a)
2. Single-serve coffee system worst case scenario (S1b) and drip-brewed coffee system best case scenario (S2a)
3. Single-serve coffee system best case scenario (S1a) and drip-brewed coffee system worst case scenario for over-preparing coffee waste (S2b)
4. Single-serve coffee system best case scenario (S1a) and drip-brewed coffee system worst case scenario for inferior bulk packaging freshness retention coffee waste (S2c)

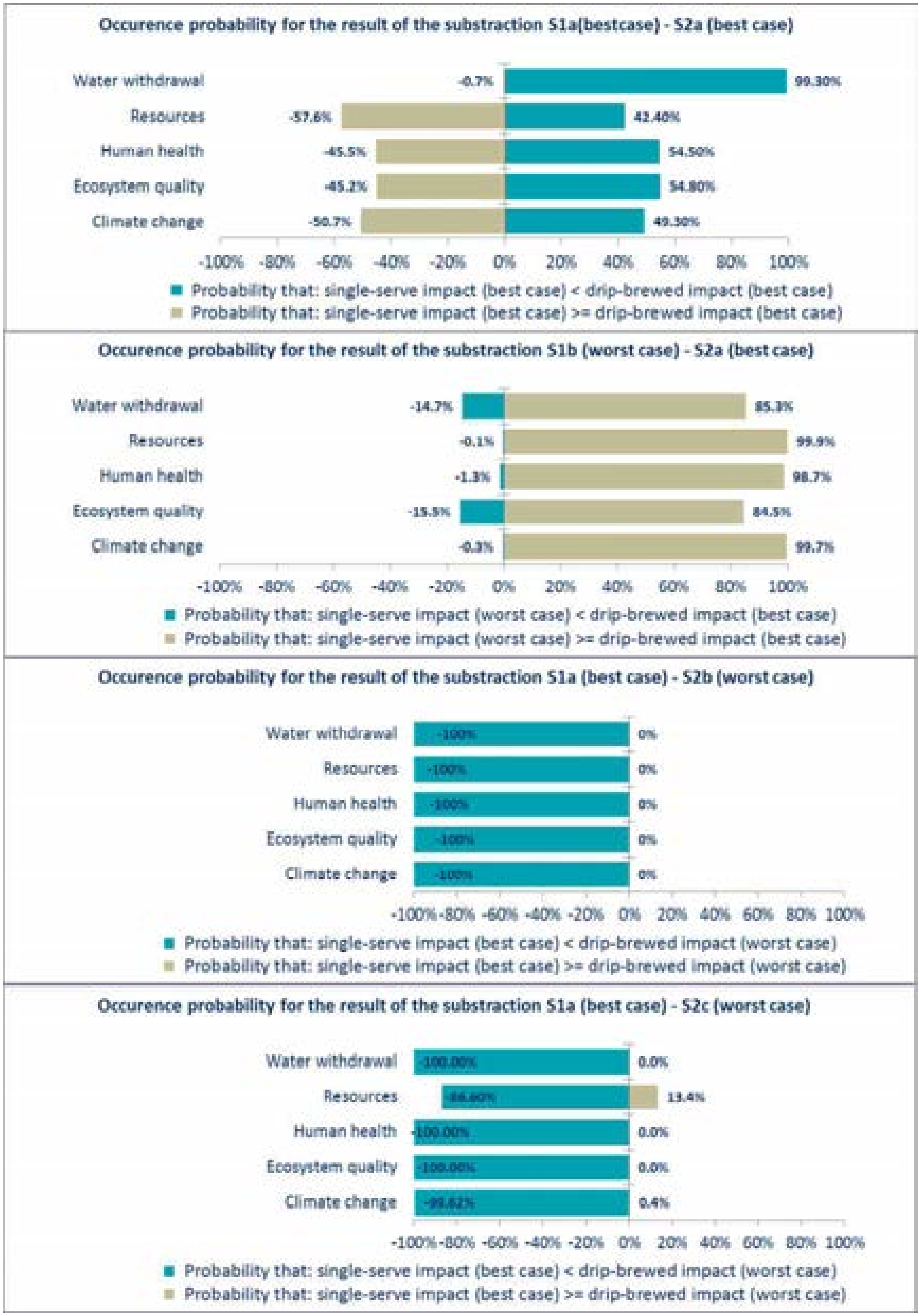

Figure 19: Monte Carlo simulation results for the comparison of the best and worst cases of the two studied coffee systems

The first uncertainty assessment (S1a-S2a) confirms that it is generally impossible to reach a confident conclusion on the environmental superiority of each option. The sole exception is the water withdrawal inventory indicator, for which it is highly probable that the single-serve coffee system performs better than the drip-filter coffee system.

In the other comparisons, the results indicate that the occurrence probability of a trend inversion between these scenarios is low.

According to the impact results presented in section 5.2, the worst case scenario for the single-serve coffee system (S1b) generates greater impacts than the best case scenario for the drip-brewed system (S2a). The Monte Carlo simulation results indicate that the occurrence probability of a trend inversion (i.e. the impacts of S1b becoming less than those of S2a) between the scenarios is low. The highest chance of inversion occurs for ecosystem quality, with a 16% chance that ecosystem quality impacts for S1b may be lower than those of S2a. Given these results, it is highly probable that S2a presents a better environmental performance than S1b. However, it is important to bear in mind that this conclusion would not be valid for the resource impact indicator if an impact assessment method that attributes greater importance to metal depletion in the calculation of the resource indicator is used instead of IMPACT2002+ (see section 5.6.2).

When the best case scenario for the single-serve coffee system (S1a) was compared to the worst case scenario for the drip-brewed coffee system considering over-preparation coffee waste (S2b), it presented a better environmental profile. The uncertainty analysis performed with the Monte Carlo simulation indicates that there is a 0% chance that a trend inversion may occur. It is therefore possible to conclude and state that scenario S1a performs better from an environmental standpoint than scenario S2b.

Finally, when comparing the best case scenario for the single-serve coffee system (S1a) to the worst case scenario for the drip-brewed coffee system considering coffee waste from lesser packaging freshness retention (S2c), S1a presents a better environmental profile. However, the uncertainty analysis performed with the Monte Carlo simulation indicates that there is a 13% chance that a trend inversion may occur for the resources indicator. In light of this, it is possible to conclude that it is also highly probable that S1a presents a better environmental performance than S2c.

Overall, while the difference in the results from the different model seems small, the uncertainty analyses support the impact assessment conclusions in most cases. This strengthens the outcome of this LCA study.

6 Discussion and implications

6.1 Key findings

Consumer habits are a key parameter that affects the life cycle impacts of coffee consumption. When comparing a single-serve coffee system to a drip-brewed coffee system, the selection of the coffee brewer, the manner in which the machine is used over its service life (e.g. time spent in on/off/ready-to-serve modes, the use of auto-power-down, keep-warm times, etc.) and coffee wasting habits (whether it be waste generated as a result of over-preparing or of inferior packaging freshness retention) all affect the environmental impact differential between the two systems.

The life cycle environmental profiles of the single-serve and drip-brewed coffee systems made it possible to conclude that the most important contributors to the overall life cycle impacts were the coffee supply and use stages, followed by the materials and production stage. The distribution stage represented 10% or less of the overall impact for all scenarios and indicators, while the end-of-life stage for both studied coffee systems did not significantly contribute to the overall life cycle impact.

This life cycle assessment revealed that the best case scenario for the drip-brewed coffee system can show a similar or even better environmental performance than the single-serve coffee system if and only if a low rate of coffee waste occurs. In fact, when the coffee waste due to over-preparing reaches 2% or when the coffee waste due to inferior freshness retention reaches 3%, the packaging gain that the bulk brewing system has over the single-serve system is offset by the greater coffee requirement.

Moreover, the study showed that although the differences in impacts from the different systems are rather small, it is possible to conclude on the environmental superiority of certain system scenarios for a given set of consumer behaviour parameters (best case scenarios) over some of the competing system's scenarios with another set of consumer behaviour parameters (worst case scenarios). More specifically, comparison results with uncertainty and data quality analyses led to the following conclusions:

- **Best case scenarios for both coffee system (drip-brewed and single-serve coffee) are considered environmentally equivalent**, except for the water withdrawal indicator for which it is highly probable that the single-serve coffee system performs significantly better.

- **It is highly probable that the drip-brewed coffee system presents a better environmental performance than the single-serve coffee system** when no coffee waste is generated through wasteful consumer habits and when a single-serve brewer with an additional ready-to-serve mode was selected.
- **The single-serve coffee system performs better from an environmental standpoint than the drip-brewed coffee system** when coffee waste from overpreparation and an efficient single-serve brewer are considered.
- **It is highly probable that the single-serve coffee system presents a better environmental performance than the drip-brewed coffee system** when including waste from lower bulk coffee packaging freshness retention and when considering an efficient single-serve brewer.

The main differences between the two studied coffee systems that are responsible for the impact differentials are the amount of required coffee to make up for wasteful consumer habits and the electricity consumption for coffee preparation, which depends on the type of brewer and the consumer's handling habits. Figure 20 summarizes the main impact differences between the two studied systems overall and per life cycle impact.

Figure 20: Main impact differences between the two studied systems

6.2 Study limitations

It is important to understand how this study was conducted so that its results and conclusions are applied appropriately. When interpreting the information presented in this report, the following limitations should be considered along with the context described in earlier sections:

- The impacts associated with die cutting seem high and unrealistic. Since the process was modeled with rough estimates, it is of poor quality. However, the results prove that it had little effect on the entire life cycle.
- Some LCI data implemented describe European operations, implying that the study may not be 100% representative of the North American context or other parts of the world (e.g. the Philippines) in terms of material manufacturing or technologies. A database of equivalent quality, transparency and robustness is not yet available for North America. Nonetheless, care was taken to adapt the processes to their geographic context by substituting grid mixes.
- Unlike an environmental risk assessment conducted in a regulatory context, which uses a conservative approach, LCA seeks to provide the best possible estimate (Udo de Haes et al. 2002). In other words, the LCIA aims to represent the most probable case and the models (of environmental contaminant transport and fate and toxic effects on biological receptors) do not attempt to maximize exposure and environmental damage.
- LCIA methodologies such as IMPACT 2002+ do not and cannot characterize the wide range of emissions released to soil, air and water by processes. However, the methodologies characterize the most well-known pollutants and, in doing so, provide the best estimate to evaluate environmental impact.

Finally, LCIA results are relative expressions and do not predict impacts on category endpoints, threshold exceedance, safety margins or risks.

6.3 Recommendations

Many recommendations were formulated in this report in order to improve the systems and results. The recommendations may also be used to improve the quality and reliability of future studies and, more importantly, guide decision-making and the development of new products and processes. Below is a summary of the main recommendations.

6.3.1 Recommendations for both coffee systems

- The sustainability and treatment of coffee cultivation can be improved by encouraging green coffee suppliers to adopt agricultural best practices (e.g. sustainable logging, optimized fertilizer application, reduced use of pesticides, etc.).
- The dishwashing impacts can be lowered by promoting good practices: raising consumer awareness of efficiently using a full dishwasher, the advantages of best-in-class dishwashers (ENERGY STAR certification) and washing with colder water.

6.3.2 Single-serve coffee system recommendations

- The heavier packaging system proved to be a hotspot in the single-serve coffee system's life cycle impacts. Consequently, efforts should focus on reducing capsule weight (for example, by exploring new and lighter materials for components).
- The energy consumption of brewers was one of the main levers for action to reduce the environmental impacts of brewing coffee.
- The service life of the brewer is also an important lever for action. A short service life can offset gains from the development of an energy-saving brewer. Thus, the development of a coffee machine with both energy-saving capabilities and an extended service life should be prioritized.

6.3.3 Drip-brewed coffee system recommendations

- Wasteful consumer habits are also one of the main levers for action to better the environmental footprint of coffee consumption. Consumer awareness of better coffee dosing for drip-filter brewer users should be encouraged to minimize food waste from coffee preparation.
- Bulk coffee packaging also proved to have design flaws as compared to single-serve coffee capsules since the same level of coffee freshness cannot be achieved, thus generating food waste and increasing the environmental burden of coffee consumption. Efforts should therefore focus on packaging design alternatives.

6.4 Conclusions

This study brought to light important information on the life cycle impacts of coffee brewing systems. It highlighted important areas for potential environmental improvements such as the development of coffee machines with better energy-saving capabilities and extended service lives and the challenge of minimizing the coffee waste generated through a bulk coffee brewing system. An investigation of consumer habits provided insights into system differences that drive impact differentials between the two studied coffee systems.

The results showed that the single-serve coffee system was disadvantaged by a larger packaging system and therefore generated greater packaging waste. Still, the set of analyses performed on the single-serve coffee system revealed that it was less sensitive to consumer habits than the drip-brewed coffee system, showing a reduction in the variability of its life cycle impact. In fact, the single-serve coffee system allows for the perfect dosing of a serving of coffee, minimizing the possibility of generating coffee waste. The maximum impact associated with this type of coffee system is therefore limited.

On the other hand, the best case scenario for the drip-brewed coffee system in which the consumer behaves cautiously has a similar or even better environmental performance than the single-serve coffee system. However, coffee dosing for the drip-brewed coffee system is done by hand and leaves room for wasteful behaviours. For a relatively low rate of coffee waste (2% due to overpreparation or 3 % due to loss of freshness), the environmental superiority of the drip-brewed coffee system is offset by the additional coffee requirements.

From this perspective, the North America-wide adoption of single-serve coffee systems by coffee consumers can be seen as an opportunity to limit coffee waste, thus presenting significant environmental benefits from a life cycle standpoint. The environmental benefits have the potential to become even greater when considering the development of coffee machines with better energy-saving capabilities and extended service lives.

Keeping in mind the modeled assumptions and study limitations, these conclusions may be used to guide decision-making and prioritize sustainability initiatives.

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8 Appendices

Appendix A – Equation for the carbon footprint of drip-brewed coffee

Coffee waste due to over-preparing and inferior freshness retention are independent parameters that can happen concurrently at different rates. The following equation can be used to calculate specific carbon footprint for a combination of the different wastage rates due to over-preparing and inferior freshness retention. This equation is valid for a 37 minutes use of the hot plate.

$$CF = 0.0125 \times W_{OP} + 0.0100 \times W_{IF} + 196$$

Where:

CF: Carbon footprint of a drip brewed coffee (g CO_2 eq.)

W_{op} :% coffee waste due to over-preparing

W_{IF}:% coffee waste due to inferior freshness

Appendix B – Additional data and assumptions

Abaca paper sheets

Once harvested, dried, tied off into hanks and shipped for processing, Abaca fibres are pulped and may be bleached before they can be made into sheets of filter material. The long strands of abaca fibre are cut and partially digested using chemical, mechanical, or a combination of techniques. Kraft, soda, alkaline sulfate and thermo-mechanical pulping are all commonly used to treat abaca fibres, so it will remain to be identified which process is used most widely to create pulp for a filter end-product. Once pulped, the abaca is generally used in conventional, Fourdrinier-type (wet-laid) paper machines to create a continuous, thin sheet of filter material that is rolled and shipped to be fluted and cut into filter form at a later stage. Heat-sealable abaca filter material is coated with a thin layer of polypropylene (PP), polyethylene (PE), or both; for single-serve capsule filters, this coating is applied around the top of the filter, where it will be sealed onto the side of the hard outer capsule. The processes used to cut and attach the paper are still unknown.

Note that some abaca filters may be surrounded by a thin film of PP/PE or other plastic in newer conventional capsule models. This film will be analyzed, weighed and categorized as a sub-component of the abaca filters for certain capsules.

PS sheets

Both studied capsules require an outer shell mostly made out of polystyrene (PS). By similar token, PS is created from petroleum and begins with crude oil extraction. Refined oil yields naphtha, which is cracked to form benzene. Benzene and ethylene are then combined to produce ethylbenzene through acid-catalyzed chemical reaction and the produce yields styrene through catalytic dehydrogenation. Finally, styrene is polymerised, and the resultant resin is extruded, via a melt-blown or spun-bonded process, into a continuous sheet that is then rolled and shipped for thermoforming.

Aluminum Lid

The aluminum lid is produced out of primary or partially recycled aluminum that undergoes a sheet rolling process to obtain an aluminum foil sheet. The sheet is coated with a heat-sealing adhesive on one surface, and is printed with the brand name and logo of the relevant company on the other. A thin layer of sealant may be applied over the printing to protect the image. The sheet is then cut into the right shape and dimensions to fit the capsules. It remains to be identified which adhesive is used, whether there is a top sealing layer on the aluminum, and so on.

Table 15: Data background

Description	Material	Process	Value	Ecoinvent process
Abaca filter	Abaca/softwood/PE		**0.28 g**	
		Wet-laid		Adapted for abaca Kraft paper, bleached, at plant/RER U (N-A Bckgrd)
				Kraft paper, bleached, at plant/RER U (N-A Background)
		Extrusion (PE)		Extrusion, plastic film/RER U (N-A Background)
		Die cutting		Electricity, medium voltage, at grid/AmN
		Packaging: carton		Solid unbleached board, SUB, at plant/RER U (N-A Background)
		Packaging: shipper		Packaging, corrugated board, FRESH fibre, single wall, at plant
		Packaging: wrap		Packaging film, LDPE, at plant/RER U (N-A Background)
		Packaging: pallet		EUR-flat pallet/RER U (N-A Background)
Aluminum lid	Al foil/PET/PE		**1 p**	
		Sheet rolling		Sheet rolling, aluminum/RER U (N-A Background)
		Calendering		Calendering, rigid sheets /RER U (N-A Background)
		Plastic extrusion		Extrusion, plastic film /RER U (N-A Background)
		Printing		Printing colour, offset, 47.5% solvent, at plant/RER U (N-A Background)
		Die cutting		Electricity, medium voltage, at grid/AmN
		Packaging: carton		Solid unbleached board, SUB, at plant/RER U (N-A Background)
		Packaging: shipper		Packaging, corrugated board, FRESH fibre, single wall, at plant
		Packaging: wrap		Packaging film, LDPE, at plant /RER U (N-A Background)
		Packaging: pallet		EUR-flat pallet /RER U (N-A Background)
Shell	PS/EVOH/PE		**1 p**	
		Extrusion		Extrusion, plastic film /RER U (N-A Background)
		Thermoforming		Thermoforming, with calendering/RER U (N-A Background)
		Calendering		
		Packaging (K-Cup)		Packaging, corrugated board, FRESH fibre, single wall, at plant
				Solid unbleached board, SUB, at plant/RER U (N-A Background)
				Packaging film, LDPE, at plant/RER U (N-A Background)
				EUR-flat pallet/RER U (N-A Background)
Inert gases	N_2		**0.43 g**	Nitrogen, liquid, at plant/RER /RER U (N-A Background)
Carton (12 units)	Solid bleach board	Box production Offset printing	*Depending on capsule systems*	Solid unbleached board, SUB, at plant/RER U (system expansion – 100% virgin material)
Shipping "crab" box	Corrugated board	Box production	**2.01 g**	Packaging, corrugated board, FRESH fibre, single wall, at plant/RER (system expansion – 100% virgin material)
Plastic wrap	LDPE	Film extrusion		Packaging film, LDPE, at plant/RER U
Pallet	Wood			EUR-flat pallet/RER

Road transport	Main transports	Transport, 53' dry van (Class 8) /AM U
Rail transport	Main transport	Transport, freight, rail, diesel/US
Water transport	Ship freight	Transport, transoceanic freight ship/OCE

Table 16: Transport of raw materials and components

Material	Total (km)	Means	Transport 1	Transport 2	Transport 3	Transport 4
Abaca fibre, Philippines	303	Origin/destination	Eastern Visayas & Bicol	Cebu		
		Truck, 53' (km)	118			
		Ferry (km)	185			
Abaca fibre, Ecuador	300	Origin/destination	In-land estate	Guayaquil		
		Truck, 53'	300			
		Freight Ship	0			
Abaca pulp, Philippines	17 587	Origin/destination	Cebu, Philippines	Cebu port	Bristol port, UK	Lydney, UK
		Truck, 53'	30	0	35	
		Freight Ship	0	17 522	0	
Abaca pulp, Ecuador	10 117	Origin/destination	Guayaquil, Ecuador	Guayaquil port	Bristol port, UK	Lydney, UK
		Truck, 53'	100	0	35	
		Freight Ship	0	9 982	0	
Abaca filter	5 731	Origin/destination	Lydney, UK	Bristol port	Boston, US	Waterbury, VT
		Truck, 53'	35	0	306	
		Freight Ship	0	5390	0	
Shell conventional cup	1284	Origin/destination	WI, VA & PA, US	Waterbury, VT		
		Truck, 53'	1284			
		Freight Ship	0			
Lid Conventional cup	1811	Origin/destination	Oshkosh, WI	Waterbury, VT		
		Truck, 53'	1811			
		Freight Ship	0			

Table 17: Secondary and tertiary packaging for 12 capsules retail unit

Packaging		Description	Mass (g)	Mass per cup (g)
Secondary	Conventional	100% recycling carton box	33.16	2.76
Tertiary		Crab box, corrugated board , 100% recycling material, contains 6 cartons per shipper (72 cups)[2]	145.04	2.01
		Plastic wrapping: LDPE film[3]	150	0.017
		Pallet: wood, contains 120 shippers per pallet (8640 cups) [2], lifetime assumed 50 uses [3]	26 240	0.061

[1]Based on direct measurements of studied capsule retail units; [2]Estimated for all studied systems based on Realcup shipper (Mother Parkers, 2014), [3]Based on Quantis' internal knowledge

Table 18: Data sources

Process	Data	Source
Capsule production life cycle stage		
Abaca fibre	Origin	FAO 2004
	Culture methods	CFC/UNIDO/FIDA 2009; FAO 2004
	Extraction	CFC/UNIDO/FIDA 2009; FAO 2004
	Yield	CFC/UNIDO/FIDA 2009
	Transport	Estimates
Pulp milling	Locations	CFC/UNIDO/FIDA 2009; Estimates
	Processing	ecoinvent
	Transport raw materials	Estimates; maps.google.ca
Abaca filter	Composition, mass	HunterConsult Incorporated, 1997; Mother Parkers 2012
	Softwood pulp	ecoinvent
	HDPE	ecoinvent; PlasticEurope, 2010
	Wet laid (paper production)	ecoinvent; Edana, 2008
	Die cutting	Estimates
	Packaging	Estimates
	Location	Assumption based on info: www.glatfelter.com
	Transport	sea-distances.com; maps.google.ca
Lid	Composition, mass	Mother Parkers 2012; ecoinvent
	Sheet rolling, calendaring	Ecoinvent
	Ink, printing	Ecoinvent

Process	Data	Source
	Die cutting	Estimates
	Packaging	Estimates, ecoinvent
	Transport	Mother Parkers 2012; maps.google.ca
Shell	Composition	Mother Parkers 2012; Mother Parkers 2014; ecoinvent
	Extrusion, thermoforming, calendareing	ecoinvent
	On site unrolling material and cutting	Mother Parkers 2014
	Packaging	Estimates; ecoinvent
	Transport	Mother Parkers 2012; maps.google.ca
Ring	Composition, mass	Mother Parkers 2014; Direct measurements
	PP	ecoinvent
	Single wrap composition and mass	Mother Parkers 2014, direct measurements
	Transport	Estimates
Capsule assembly	Nitrogen flush	Mother Parkers 2014
	Electricity assembly and filling	Mother Parkers 2014
Distribution life cycle stage		
Packaging	Carton box (12 units)	Direct measurements from marketed carton for each systems
	Shipment box (corrugated)	Direct measurements from Mother Parker's shipper for all systems
	Plastic wrap	Quantis - Internal knowledge
	Pallet	Quantis - Internal knowledge
Delivery	Loading	Quantis - Internal knowledge
	Distribution profiles	GMCR 2011; Estimates; ecoinvent
	Storage, distribution center electricity requirements	Quantis - Internal knowledge
	Storage duration, on-shelf time	Estimates, personal communications
	Retail strategy (online/store)	Estimates
Use life cycle stage		
	Usage frequency of single-serve brewer	ENERGY STAR, 2011
	Volume of brewed coffee	Keurig Green Mountain, inc. 2014b
	Single-serve brewer production and lifetime	European commission, 2011
	Energy consumption of Single-serve brewer	ENERGY STAR, 2011
	Ceramic mug	IKEA 2014
	Dishwasher: production	Quantis internal
	Dishwasher: Lifetime, loading, electricity & water use	Humbert et al., 2009
End-of-life		
	Lifetime single-served capsule	Mother Parkers 2012
	Landfill/incineration ratio	EPA 2010
	Waste-to-energy from incineration	ecoinvent
	Recycling rates for packaging materials	EPA 2010, PPPEC 2011

Process	Data	Source
	Recycling rates for Ecocup	Estimates; EPA 2012
	System expansion for recycling	ecoinvent
	Composting of PLA and coffee	Quantis - Internal knowledge

Appendix C – Description of impact categories

Human health

Impact that can be caused by the release of substances that affect humans through acute toxicity, cancer-based toxicity, respiratory effects, increases in UV radiation, and other causes; an evaluation of the overall impact of a system on human health has been made following the human health end-point in the IMPACT 2002+ methodology, in which substances are weighted based on their abilities to cause each of a variety of damages to human health. These impacts are measured in units of disability-adjusted life years (DALY), which combine estimations of morbidity and mortality from a variety of causes.

Ecosystem quality

Impairment from the release of substances that cause acidification, eutrophication, toxicity to wildlife, land occupation, and a variety of other types of impact; an evaluation of the overall impact of a system on ecosystem quality has been made following the Ecosystem quality endpoint IMPACT 2002+ methodology, in which substances are weighted based on their ability to cause each of a variety of damages to wildlife species. These impacts are measured in units of potentially disappearing fractions (PDF), which relate to the likelihood of species loss.

Resources

Depletion caused when nonrenewable resources are used or when renewable resources are used at a rate greater than they can be renewed; various materials can be weighted more heavily based on their abundance and difficulty to obtain. An evaluation of the overall impact of a system on resource depletion has been made following the resources end-point in the IMPACT 2002+ methodology, which combines nonrenewable energy use with an estimate of the increased amount of energy that will be required to obtain an additional incremental amount of that substance from the earth based on the Ecoindicator 99 method (Goedkoop and Spriensma 2000).

Climate change

Alterations in the statistical distribution of weather patterns of the planet over time that last for decades or longer[1]; Climate change is represented based on the International Panel on Climate Change's 100-year weightings of the global warming potential of various substances (IPCC 2007). Substances known to contribute to global warming are weighted based on an identified global warming potential expressed in grams of CO_2 equivalents. Because the uptake and emission of CO_2 from biological sources can often lead to misinterpretations of results, it is not unusual to omit this biogenic CO_2 from consideration when evaluating global warming potentials. Here, the recommendation of the PAS 2050 product carbon footprinting guidance is followed in not considering either the uptake or emission of CO_2 from biological systems and correcting biogenic emissions of other gasses accordingly by subtracting the equivalent value for CO_2 based on the carbon content of the gas (BSI 2008).

Water withdrawal

Sum of all volumes of water used in the life cycle of the product, with the exception of water used in turbines (for hydropower production). This includes the water use (m^3 of water needed) whether it is evaporated, consumed or released again downstream. Drinking water, irrigation water and water for and in industrialized processes (including cooling water) are all taken into account. It considers freshwater and sea water.

[1] Quantis definition

Appendix D – Detailed results and life cycle inventory

The content of this appendix is included in the following file

« Appendix_D_Drip_vs_singleserve_results_ISOCOMPLIANT_Final.xlsx »

Appendix E – Critical review report

The content of this appendix is included in the following file

« Critical_Review_Report_Final_Verdict.pdf »