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Life cycle assessment based optimization of scenarios of reusable glass bottles using context-specific key parameters

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ABSTRACT

Reusable glass bottles are experiencing a resurgence, driven notably by societal concerns and regulations. While single-use glass bottles generally have higher environmental footprint compared to plastic bottles, reusable systems could reduce both impacts related to single-use (e.g., climate change, energy consumption) and plastics (e.g., microplastic pollution). The environmental benefits of reusable bottles can vary across systems and this can be overlooked by stakeholders who rely on generic results for communication and a limited number of parameters to design their systems. This study addresses this gap by developing a systematic analysis of the variability of life cycle assessment results, within the specific case study of a new beverage. As a result, a list of key parameters to consider for the specific case study is set, enabling to propose targeted mitigation strategies. The commonly used generic key parameters are complemented with context-specific key parameters, empowering stakeholders to develop efficient systems and communicate their environmental performance accurately. Different configurations are likely to be influenced by other key parameters, and require specific mitigation strategies. In this perspective, stakeholders need assistance in: (1) designing context-specific strategies, and (2) translating – complex and plural – life cycle assessment results into actionable decisions.

1. Introduction

Food packaging has evolved through distinct historical phases. The package was initially developed to mitigate external threats able to deteriorate the product (e.g., development of moisture, degradation of the aspect or taste) (Risch, 2009). Over time, additional functionalities have complemented the initial protective role (e.g., facilitating transportation and storage, supporting product and brand communication, and extending the product's shelf life) (Lockhart, 1997; Sacharow et al., 2006). European regulations, which aim at reducing the environmental impact of packaging, mean that in addition to these functions, their design must also allow for reuse, recycling, and energy recovery (European Commission, 1994; Grundey, 2010). The multiplicity of functions and constraints implies complex decision-making when choosing between packaging solutions and designing optimal food packaging.

Glass containers dominated the beverage market until the late 1960s (Berger, 2005), especially for liquids but finally became economically uncompetitive, too heavy and fragile, compared to new - metal or plastic - packaging. Glass then lost market share to the advantage of metals and mostly plastics, easier to produce, lighter and less expensive. Glass however remained the reference for high-value products thanks to a better reputation in preserving taste and flavour (Berger, 2005). Moreover, glass is seen as a possible solution to end with plastics since plastics are pointed out as responsible for multiple pollution in the last years (Andrady, 2011; Rhodes, 2018). Nevertheless, glass is associated with significant environmental impacts. Manufacturing glass bottles generates significant greenhouse gas emissions and consumes substantial energy and resource (Amienyo et al., 2013; Brock and Williams, 2020). These impacts are reduced if the bottles are returned and reused compared to single-use (Mata and Costa, 2001; Landi et al., 2019; Stefanini et al., 2021). In line with the growing emphasis on circularity in resource use, reuse of glass bottles is experiencing a resurgence in countries where it had declined in last decades. European Commission

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Abbreviations: LCA, Life Cycle Assessment; LCI, Life Cycle Inventory.

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actively promotes refillable beverage packaging, including glass, and underscores the need for public initiatives to incentivize reuse systems (European Commission, 2009). Motivated by the goal of eliminating plastics packaging by 2040 and current economic considerations, France has set ambitious targets for reusable packaging, aiming for 10% market share by 2027 (French Governement, 2022). To effectively understand the relationship between packaging, waste generation and environmental consequences, established methods for quantifying these impacts have been extensively developed and employed for decades.

Life Cycle Assessment (LCA) was developed in the 1990s to quantify the direct and indirect impacts of a system (product, service) along its life cycle. It aims to quantify various potential impacts on the environment (e.g., Global Warming Potential, Acidification Potential, Fossil Resource Use). It has been widely applied to all activity sectors and is guided by international standards and guidelines (ISO, 2006a; ISO, 2006b; JRC et al., 2010). LCA has been largely applied to study the environmental impacts of food packaging notably to drinks packaging (Brock and Williams, 2020). In comparative LCA, single-use glass bottles are generally more impacting than single-use plastic bottles (Amienyo et al., 2013; Stefanini et al., 2021; Saleh, 2016; Dhaliwal et al., 2014). However, this is to moderate, regarding the lack of appropriate indicators in LCA to assess pollution related to plastics despite current methodological developments (Boucher et al., 2020; Pauna and Askham, 2022; Lavoie et al., 2022; Corella-Puertas et al., 2022). In particular, potential impacts of plastic leakage on biota are not assessed (Corella-Puertas et al., 2023). Indeed, (Stefanini et al., 2021)advances that while reusable glass bottles are more impacting than PET bottles along common impact categories, it has less impacts on the developed marine litter indicator (Stefanini et al., 2021). Several LCA studies show that the benefits of reusable glass bottles compared to single-use glass bottles (Mata and Costa, 2001; Landi et al., 2019; Stefanini et al., 2021) depend on key parameters. However, no systematic study on those key parameters was identified in the literature, neither a generic list of those key parameters. The number of uses of the bottle is always found as a critical parameter when some other parameters are punctually named (e.g. transport modes and distances, energy and water consumptions at cleaning, mass of the containers).

Literature shows that the environmental benefits of reusable bottles can vary from a system to another (ADEME et al., 2018). Without a systematic analysis, the sources of this variability remain poorly understood, hindering efforts to optimize and accurately assess the systems specifically. To achieve a more comprehensive environmental assessment and encourage virtuous solutions, it is crucial to incorporate more context-specific considerations, particularly during the early stages of the development of new regional products. This would facilitate to: (1) better optimization of the systems, from the environmental perspective, by considering the sources of impacts in a contextualized way and (2) enhanced communication of the associated benefits. Current commercial arguments employed, for example in France, to promote reusable bottles often rely on two studies (Deroche Consultants, 2009; ADEME et al., 2018) regardless of the context of their implementation. (Deroche Consultants, 2009) studied a specific mature system focusing on a single beer producer. (ADEME et al., 2018) studied ten systems of reusable bottles in France, with contrasted results among the systems. In Supplementary Material 1 (https://doi.org/10.57745/LBOEGQ), we analyzed the environmental information provided on the websites of 10 French regional companies referencing the same arguments (i.e., until −79% CO_2 emissions, −75%/76% energy use and −33%/51% water use). These claims are not inherently misleading as, most of the time, the source is cited and the message is qualified (e.g., “until […]”, “in a regional context, with a sufficient number of reuses” or “for 19 uses, from […]”). However, stakeholders express the wish for improved communication regarding the specific impacts of their individual systems.

This paper investigates, using a theoretical case study (i.e., an innovation beverage under development), the necessity of considering context-specific parameters when developing and justifying strategies for reusable bottles. The environmental impacts of two reference scenarios are compared: single-use (Sref-SU) and reusable bottles (Sref-RET). Then, with the objective of guiding potential actions to enhance the benefits of Sref-RET, the key parameters influencing its environmental impacts are determined using contribution analysis and two types of sensitivity analysis. In addition to one-at-a-time sensitivity analysis (OAT-SA) on three key parameters usually found in the literature (i.e., number of bottle uses, mass of the bottles and distance from drink production to retail), Global Sensitivity Analysis (GSA) is applied to explore potential system-specific key parameters influencing the environmental impacts. The identification system-specific key parameters enable the proposal of alternative scenarios, whose environmental impacts are then compared to the reference scenarios. The results are used to discuss the critical need for contextualization when implementing reusable bottle systems (transposable to other LCA studies) and current barriers for stakeholders to achieve this (i.e., need for more accessibility and simplification of LCA).

2. Materials and methods

2.1. Case study

This paper refers to the development of a reusable bottle strategy in a theoretical case study: an innovative whey-based drink under development in the context of H2020 FAIRCHAIN project. The case study aims to develop a new valorisation route for whey, a coproduct of cheese manufacturing. It stands in Jura mountains, in Region Bourgogne Franche-Comté, in France. In this region, Protected Designation of Origin (PDO) cheeses (in particular Comté and Morbier) are produced. The production yields two distinct types of whey: sweet whey and acidified whey. Sweet whey, representing approximatively 90% of the initial volume of milk, is obtained at the beginning of the cheesemaking process (curdling stage). It is currently well valorised, notably to produce protein powders for infant formulas. Acidified whey constitutes a smaller portion, obtained later during the cheese pressing stage. Currently, in the factory investigated, acidified whey is sent to a wastewater treatment plant. One objective of the FAIRCHAIN project is then to create an innovative drink, creating added value to the non-used whey. In addition, the project envisions local distribution of the beverage, using reusable bottles. This paper specifically addresses the environmental impacts of the distribution stage of the beverage, excluding its production from the system boundaries.

2.2. LCA methodology

The four methodological steps of LCA (ISO, 2006a; ISO, 2006b) are followed in this work: goal and scope definition (i.e. objectives, geographical and temporal boundaries, functional unit and system boundaries), Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation. While the present study is not a formal LCA of a beverage, hypotheses were questioned in regards with Environmental Product Footprint guidance for beverages (FoodDrinkEurope, 2022).

2.2.1. Goal and scope definition

The objectives of the study were to (1) compare scenarios based on single-use and reusable bottles for the specific case under study; (2) conduct a comprehensive analysis of the variability and uncertainty and (3) propose alternative scenarios, from an eco-design perspective, to minimize environmental impacts, based on sensitivity analysis methods. An attributional approach was employed.

2.2.2. System boundaries and functional unit

The system boundaries included all life cycle from beverage bottling to consumer (Fig. 1): primary packaging material, manufacturing, transport from production sites and waste management (for bottles, caps

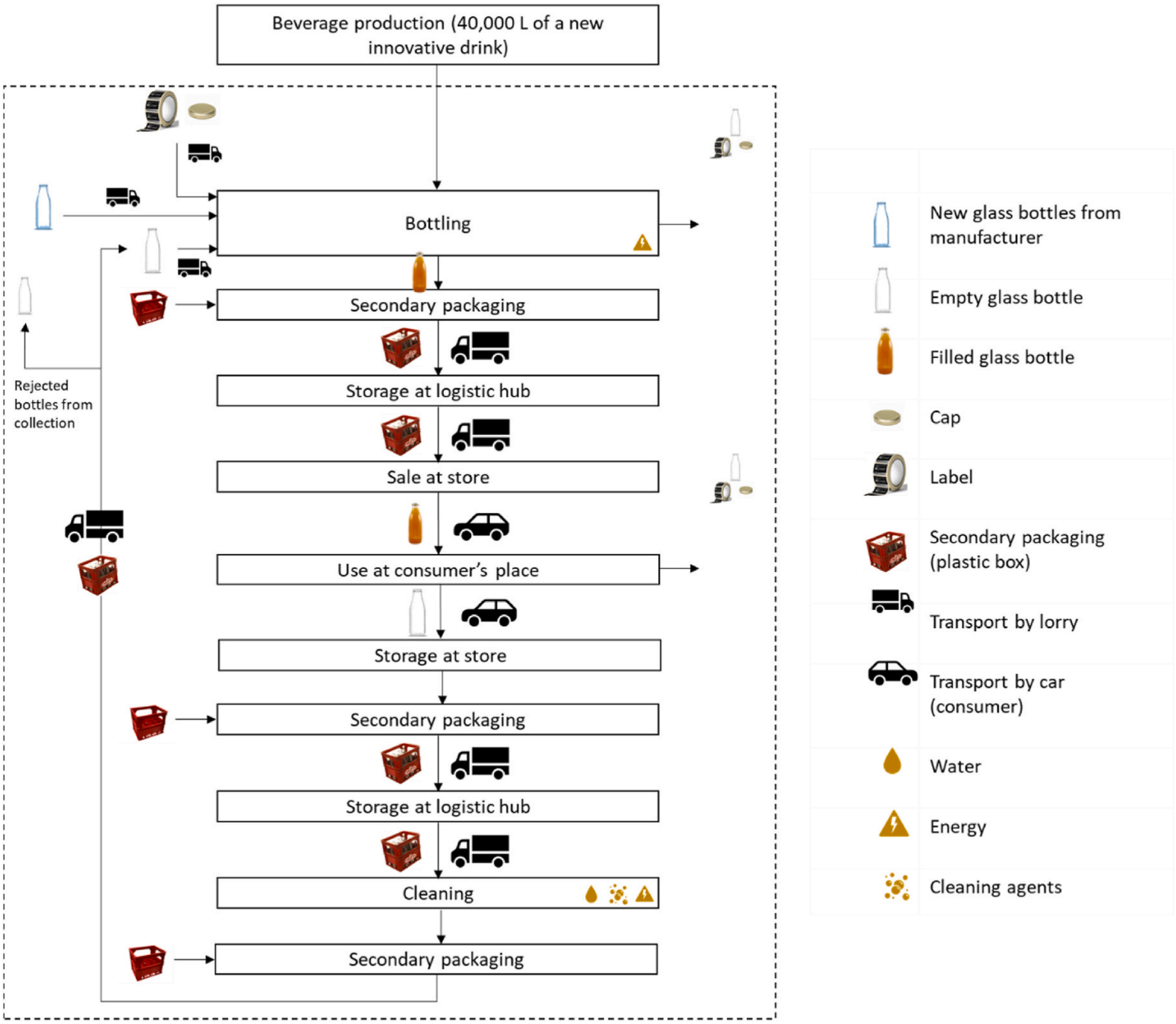


Fig. 1. A Simplified flow diagram of the system studied.

and labels), bottling, cleaning (for reusable bottle scenarios). All relevant transport steps were included in the study, as well as secondary packaging used for reusable bottles. It excludes the production of the beverage itself (raw material acquisition, process), focusing on downstream.

The functional unit was defined as “delivering 40,000 L of an innovative whey-based beverage to the consumer in 1-L containers conferring hygienic conditions”, corresponding to one-year production planned for the innovative drink.

2.2.3. *Life Cycle Inventory*

2.2.3.1. Common characteristics in the two reference systems. This section describes the common aspects of the reference system for single-use bottles (Sref-SU) and the reference system for reusable bottles (Sref-RET). Subsequent sections will detail the specificities of Sref-RET. Most of the background data originates from Ecoinvent 3.8 (details regarding the utilized processes are provided in Supplementary Material 2 (https://doi.org/10.57745/LBOEGQ)). As the study is based on an innovation under development, the reference systems were initially defined as potential scenarios, in discussion with the relevant project experts (one national – PETREL – and one local – J’aime Mes Bouteilles – actors). The study precisely aims to include the environmental perspective in future implementations.

As an ambient-stable beverage, no cold procedure is required to ensure its preservation. Weekly production amounts 1000 L, bottled in 1-L white-glass bottles in Poligny (France). Two bottling options are investigated: single-use bottles (weighting 390g) and reusable bottles (weighting 627g, designed for higher durability) (Table 1). Bottling incurs an electricity consumption of 0.033 kWh per bottle (Table 2). In absence of data for the drink under development that was estimated from (Amienyo et al., 2013) that could be overestimated for the present case study, as including more stages than filling. Aluminium caps (weighting 1.55g) and polypropylene labels (weighting 1.80g) are used.

Table 1
Packaging data for Sref-SU and Sref-RET.

Parameter	Sref-SU	Sref-RET	Unit
Glass bottle			
Volume	1	1	L
Mass	390	627	g
Initial loss	5	5	%
Return rate	NA	66	%
Rejected from collection	NA	1	%
Cap			
Mass	1.55	1.55	g
Initial loss	5	5	%
Label			
Mass	1.8	1.8	g
Initial loss	5	5	%
Plastic box (secondary packaging)			
Mass	2.1	2.1	kg
Capacity	12	12	Bottles/box
Number of uses	250	250	times

Table 2

Process data for Sref-SU and Sref-RET.

Parameter	Amount	Unit
Bottling		
Electricity	0.033	kWh/bottle
Cleaning		
Electricity	0.01	kWh/bottle
Water	0.5	L/bottle
Cleaning agent	0.008	kg/bottle

Bottles are sourced from a national glassmaker located 122 km away in Châlon-sur-Saône, representing the closest glassmaker from production site, and delivered by a 19t lorry (Table 3). Secondary packaging was considered for the new bottles. They are considered to be delivered in 940-bottles wood pallets (reused 28 times), in which 20 tiers are separated by plastic divider (used 1 time). The pallet is protected by a plastic cover. Caps and labels are respectively produced in Epernay (350 km) and Lyon (170 km) and assumed to be delivered by a 19t lorry. A 5% manufacturing scrap rate (initial loss) is assumed for all primary packaging components, i.e., bottles, caps and labels. Secondary packaging was not considered for caps and labels. Weekly, the beverages are transported by a 19t lorry, in which they are considered grouped with other products to a logistic hub, located 32 km far from the production site, then to four stores of the company, located 100 km far from the logistic hub at the maximum. In the absence of forecasts of the repartition of the sales among the four stores, the maximal distance is taken as hypothetical distance from logistic hub to store for the two scenarios. Bottles are transported using reusable plastic boxes as secondary packaging, with a 12-bottles capacity, and intended for 250 lifetime uses. Both material, manufacturing and end-of-life are considered for primary and secondary packaging. In particular, the end-of-life of the bottles is considered for single-use reusable bottles. The beverages sold locally to consumers, assumed to travel 4 km by car for purchasing in average. A parameter is implemented to allocate a portion of the consumers trip's environmental impact to the beverage, based on economic allocation (as a hypothesis, it is set to 10% in reference scenarios: the price of the 1-L drink is set to 5 euros, and the average shopping basket is set to 50 euros). The consumers' end-of-life management of all packaging is considered to follow the French context by using corresponding background data from Ecoinvent for waste management (French-specific for glass and plastics and Europe-specific for metals). Transport modes are associated to a default load in Ecoinvent database (Spielmann and Scholz, 2005). To be able to modulate it in alternative scenarios, a load ratio was introduced in the model. It is set to 1.0 for the two reference scenarios (i.e. equivalent to Ecoinvent).

2.2.3.2. Specificities of the reference system for reusable bottles (Sref-RET). This section describes the specific data employed to modelling and analysing the reference system for reusable bottles. Due to the lack of field data in this theoretical study, the return rate is set to 66% for Sref-RET as the average value observed in multiple systems assessed in a recent French study (ADEME et al., 2018). The assumption is that consumers return bottles during subsequent purchases in the store. Consequently, to avoid double-counting, no additional impact related to the return of the empty bottle is accounted, as the round-trip of the consumer to buy the drink is already accounted for. A parameter (designated as “rejected rate at collection”) accounts for the fraction of collected bottles deemed unsuitable for reuse (i.e. rejected). It is assigned a value of 1% for Sref-RET, based on data provided from the stakeholder. This rejected rate is coherent with those provided in literature for French systems, ranging from 0.48% to 2% (ADEME et al., 2018). This parameter was applied to every bottle cycle. Bottles are then collected during the delivery of new beverages and transported back to the logistic hub where they are centralized. From there, the bottles are conveyed by a 19t lorry to a cleaning facility located 100 km away. The cleaning process utilizes 0.5 L of water, 0.008 kg of soda ash and 0.01 kWh of electricity per bottle. When cleaned, bottles are returned to the beverage production site.

Table 3

Transport data for Sref-SU and Sref-RET.

Parameter	Distance (in km)	Mode
Transport from bottle maker to drink producer	122	19t lorry
Transport from cap maker to drink producer	350	19t lorry
Transport from label maker to drink producer	170	19t lorry
Transport from bottling to logistic hub	32	19t lorry
Transport from store to consumer	4	Passenger car
Transport from logistic hub to cleaning	100	19t lorry
Distance from logistic hub to stores (maximum)	100	Light commercial vehicle

2.2.3.3. Input parameters of the LCA model for Sref-RET. The LCA model employs 55 input parameters to calculate a single environmental impact for Sref-RET. From these input parameters, 30 are foreground data, common to all impact categories (e.g., the mass of the bottles) and 25 are background processes which value changing from an impact category to another (e.g., the amount of CO_2 eq per kg of glass). A detailed list of these 55 parameters is provided in the following.

2.2.3.3.1. Details on the number of uses. The number of reusable bottles used is the most tested parameter with OAT-SA in the literature. In our model, the number of uses is derived from two inputs parameters: the return rate and the rejection rate at collection. In practice, the actual number of uses deviates from the theoretical number of times a bottle can be used (based on technical considerations). The number of uses depends on the consumer's willingness to return the bottles (reflected by the return rate) and the proportion of the bottles deemed unsuitable for reuse (represented by the rejection rate at collection). The number of uses can be calculated as follows (Equation (1)):

$$\textit{number of uses} = \lim_{n\to\infty} \frac{n^*X}{X + n^*(X^*(1-(\textit{return rate}^*(1-\textit{rejection rate}))))} = \frac{1}{(1-(\textit{return rate}^*(1-\textit{rejection rate})))}$$

Where X is the quantity of drink sold each time and n is the number of sales in time.

Equation (1). calculation of the number of uses from return and rejection rates.

A limitation of some studies is the use of unrealistic theoretical numbers of uses for reusable bottles. For instance, prior studies have assumed 20 refills (Deroche Consultants, 2009; Boutros et al., 2021), corresponding to a 96% return rate (with 1% bottles rejected) based on Eq (1). However, such high return rates are rarely observed in practice, except under specific circumstances where the consumer is not directly responsible for returning the bottles. This occurs in catering or home delivery services, where bottles are delivered and collected by a third party (according to experts interviewed). The study conducted by ADEME in 2018, reported return rates ranging from 12% (for a non-mature system) to 97% (ADEME et al., 2018).

2.2.3.3.2. Details on the mass of the bottles. Several studies assume that the mass of reusable bottles is equal to – same volume – single-use bottles. This may lead to an underestimation as other sources estimate reusable bottles to be 10% heavier than their single-use equivalents (that would correspond to 429g in our case as the mass of single-use bottles is 390g). In absence of definitive information about the specific bottles that will be used, in Sref-RET, we opted for overestimation, setting the mass to 627g, extrapolating from a 75 cl white-glass bottle certified as reusable by the experts associated to the project. As no such standard bottle is currently available in France, this estimation provides a conservative – probably overestimated – upper bound.

2.2.4. *Life Cycle Impact Assessment*

Attributional LCA is computed using SimaPro 9.4.0.2, (Pre-sustainability and SimaPro, 2023) and all 16 impact categories of Ecological Footprint 3.0 (EF3.0) characterization method (Fazio et al., 2018) were considered: climate change (CC), ozone depletion (OD), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity non cancer (Htnc), human toxicity cancer (Htc), acidification (AP), eutrophication freshwater (Epf), eutrophication marine (Epm), eutrophication terrestrial (Ept), ecotoxicity freshwater (Ecotox), land use (Lu), water scarcity (Ws), resource use fossils (Ruf) and resource use minerals and metals (Rum).

2.2.5. *Sensitivity analysis*

To confront our results to existing literature, we firstly conducted One At a Time Sensitivity Analysis (OAT-SA) on key parameters identified as sensitive parameters in LCA of reusable bottle systems: the number of uses (to which we preferred the return rate, easier to measure), the mass of the bottle and the distance from beverage producer to the retail location. The selection of these parameters is informed by a comprehensive review of existing literature (Table 4).

To complement the limitations of OAT-SA, which assesses sensitivity of a single parameters while holding all others constant, we performed a Global Sensitivity Analysis (GSA). This approach enables the simultaneous examination of variability in all input parameters. The objectives are to (1) assess the uncertainty of our results and (2) identify the input parameters that significantly contribute to the variability of the results, in addition to those commonly cited and used for OAT-SA, and considering the interactions between parameters. GSA was conducted considering all 55 input parameters of the LCA model (detailed in Table 5). The SALib Python library was employed. Uncertainty is estimated with Monte Carlo simulations following Saltelli's sampling method (Saltelli et al., 2010). The sample size is 57,344 simulations, corresponding to a use of SALib library with $D = 55$ input parameters and $N = 512$: number of simulations = $N*(2*D+2)$. Subsequently, GSA was performed using Sobol indexes (Sobol, 2001). Sobol indexes aims to estimate the degree of variability of the output attributable to each input parameter. Sobol's method calculates three types of indexes: (1) first-order index, S_i, which gives the contribution of each parameter i to the variance of the output; (2) N-order index, $S_{ij\ \dots\ n}$, which gives the contribution of the interaction between n parameters (excluding their individual effects) and (3) total index, ST_i, that gives the contribution of one parameter i, including its interactions with all other parameters. The most the sum of first-order indices tends towards 1, and the most variance is explicated (without considering the interactions). In some cases, the contribution of interactions is minor and considering first-order indices is sufficient. This was verified for our model.

Each parameter is associated to a statistical distribution. The parameters and distributions set for climate change are provided in Table 5. Distributions are based on expert's knowledge and literature. Further details are available in Supplementary Material 3 (https://doi.org/10.57745/LBOEGQ).

2.2.6. *Alternative scenarios*

Theoretical alternative scenarios are derived from contribution analysis of Sref-RET and sensitivity analysis (Fig. 2). These scenarios aim to illustrate the usefulness of considering context-specific parameters when eco-designing the implementation of reusable bottle systems. They are built on the basis of different mitigation strategies to minimize the impacts. A detailed description of these scenarios and their associated environmental impacts is provided in the Results section. Furthermore, to assess the potential for unforeseen environmental drawbacks, worst-case scenarios are also explored for both single-use and reusable bottles. These scenarios investigate the potential environmental impact if the systems are not optimized, and their outcomes are compared to those of the reference scenarios.

3. Results

3.1. *Results of the Life Cycle Impact Assessment (LCIA) of the two reference scenarios*

This section describes the main results of the LCIA. More details on numerical values are provided in Supplementary Material 4 (https://doi.org/10.57745/LBOEGQ).

3.1.1. *Comparison of the two reference scenarios*

Fig. 3 presents the environmental impacts associated with the two reference scenarios: Sref-SU (single-use bottles) and Sref-RET (reusable bottles with return and rejection rates respectively equal to 66% and 1%). Sref-RET generates less impacts than Sref-SU, across most impact categories, ranging from −1.8% for human toxicity - cancer to −21.9% for land use (median = −9.2%). Only water scarcity shows a slight increase of +0.9% due to the use of water to clean the bottles, not compensating the water used to produce new bottles with low return rate. While the observed differences are relatively small, they highlight the potential environmental benefits of reusable bottles. However, eco-designing the implementation scenarios for reusable bottles seems necessary to ensure and maximize their environmental advantages compared to single-use options. Further analysis of the contribution for Sref-RET, aiming at identifying the main impacting sub-parts of the system to be considered from an eco-design perspective, is therefore necessary.

3.1.2. *Contribution analysis of the reference scenario for reusable bottles*

Fig. 4 depicts the relative contribution of each sub-part of Sref-RET, for the 16 impact categories of EF3.0 method. For each impact category (in line), the bar size for a given sub-part (in column) is proportional to its contribution to the total impact. The contribution analysis identifies three major contributors to the total impacts, for all impact categories (Fig. 4): (1) transportation of the beverages from the logistic hub to stores, (2) glass bottles (including material and manufacturing) and (3) transportation of the beverages by the consumer from the store to home. Water and soda used for cleaning contribute to water use. Focusing on climate change, the three mentioned stages contribute for about 90% of the total impact with respectively 34% for the transportation of the beverages to stores, 30% for the consumers' trip and 23% for the bottle production. Minor contributions are related to secondary packaging for the collection (2.3%) and to the caps production (1.8%). More details on numerical results, and other minor contributions are provided in Supplementary Material 5 (https://doi.org/10.57745/LBOEGQ).

These results lead to several key recommendations for minimizing the environmental impacts associated to Sref-RET.

- Bottles: the environmental impacts of bottles are directly proportional to both their mass (the lower the mass of one bottle, the lower the impact) and the number of bottles. The latter is itself influenced by the return rate: the higher the return rate (i.e., the number of use), the lower the impact. Impact equations are provided in Supplementary Material 2 (https://doi.org/10.57745/LBOEGQ) for more details. According to literature, those two parameters could be interlinked: heavier bottles may offer a higher theoretical number of uses due to less breakability.
- Transportation from logistic hub to stores: the current transportation scheme for supplying beverages to the four stores lacks optimization in terms of distance and mode. Alternative scenarios should explore optimization strategies, including shared transportation with other companies. This could involve switching from light commercial vehicles to heavier 19t lorries for improved efficiency.

Table 4

List of parameters tested as sensitivity analysis in literature. For each parameter listed, the sensitivity of the results is indicated if the parameter is analyzed in the publication. The cell remains empty if the parameter is not analyzed. The names of the most analyzed parameters are bolded in the table.

Parameter	Deroche (2009) (Deroche Consultants, 2009)	Ponstein et al. (2019) (Ponstein et al., 2019)	Boutros et al. (2021) (Boutros et al., 2021)	Ferrara and De Feo (2018) (Ferrara and De Feo, 2018)	Cleary (2013) (Cleary, 2013)	Amienyo et al. (2013) (Amienyo et al., 2013)	Detzel and Mönckert (2009) (Detzel and Mönckert, 2009)	Simon et al. (2016) (Simon et al., 2016)	Mata and Costa (2001) (Mata and Costa, 2001)	Tua et al. (2020) (Tua et al., 2020)	Saleh (2016) (Saleh, 2016)	ADEME et al. (2018) (ADEME et al., 2018)
Energy consumption at bottle manufacturing	Small											
Type of energy at bottle manufacturing	Small											
Recycling rate	No			Med.		For PET only					High	
Type of pallets	No											
Number of uses	High	High	High	High	Small	High	Small		High	Small		High
Mass of the bottle		High	Small							No		Small
Distance to consumer			For PET only									
Functional unit			No									
Distance from glass manufacturing to producer					Small							
Distance from drink producer to retail				High		Small	High			High		Med.
Refrigeration at retail						High						
Refund rate										No		
Distance from cleaning to drink production												Med.
Water consumption at cleaning												High

Table 5

Input parameters (n = 55) used for the Global Sensitivity Analysis for Climate Change impact category, with selected distributions and related parameters[1]. For more details, refer to supplementary_file_3 (unif is for uniform distribution and norm is for normal distribution).

Input parameter name	Distribution	First bound	Second bound	Unit
unit_glass	unif	0.83467824	0.90827015	kg CO_2 eq/kg
unit_cap_material	unif	1.7125279	19.818046	kg CO_2 eq/kg
unit_cap_process	norm	0.72935852	0.072935852	kg CO_2 eq/kg
unit_label_material	norm	1.9823888	0.19823888	kg CO_2 eq/kg
unit_label_process	norm	0.17620344	0.017620344	kg CO_2 eq/kg
unit_transport_new_bottles	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_new_caps	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_new_labels	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_electricity	norm	0.024262253	0.0024262253	kg CO_2 eq/kWh
unit_transport_drinks_from_bottling_to_hub	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_drinks_from_hub_to_sale	norm	1.8616715	0.18616715	kg CO_2 eq/tkm
unit_transport_consumers	norm	0.33504641	0.033504641	kg CO_2 eq/km
unit_waste_glass	norm	0.025676058	0.0025676058	kg CO_2 eq/kg
unit_waste_cap	norm	0.042140962	0.0042140962	kg CO_2 eq/kg
unit_waste_label	norm	1.5293586	0.15293586	kg CO_2 eq/kg
unit_secondary_packaging_box	unif	0.380072792	5.4079882	kg CO_2 eq/box
unit_transport_used_bottles_from_sale_to_hub	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_used_bottles_from_hub_to_cleaning	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_clean_bottles_from_cleaning_to_hub	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_transport_clean_bottles_from_hub_to_sale	norm	0.16296828	0.016296828	kg CO_2 eq/tkm
unit_water_for_cleaning	norm	0.00033156175	0.000033156175	kg CO_2 eq/kg
unit_soda	norm	1.38	0.138	kg CO_2 eq/kg
unit_VMF_pallet	norm	5.7622393	0.57622393	kg CO_2 eq/p
unit_divider	norm	0.95018198	0.095018198	kg CO_2 eq/kg
unit_plastic_cover	norm	3.4987028	0.34987028	kg CO_2 eq/p
mass_bottle	unif	0.400	0.800	kg
initial_loss_bottles	norm	0.05	0.005	None (%)
return_rate	unif	0.30	0.60	None (%)
rejected_rate_from_collection	unif	0.01	0.3	None (%)
mass_cap	norm	1.55	0.155	g
initial_loss_caps	norm	0.05	0.005	None (%)
mass_label	norm	1.8	0.18	G
initial_loss_labels	norm	0.05	0.005	None (%)
distance_from_glassmaker_to_drink_producer	norm	122	12.2	km
distance_from_caps_maker_to_bottling	norm	350	35	km
distance_from_labels_maker_to_bottling	norm	170	17	km
electricity_one_bottling	norm	0.0186	0.00186	kWh/bottle
distance_from_bottling_to_hub	norm	32	3.2	km
distance_from_hub_to_sale	unif	50	150	km
distance_empty_bottles_from_hub_to_sale	unif	50	150	km
distance_from_hub_to_cleaning	unif	50	150	km
load_ratio_drink_transport	norm	1	0.1	None (%)
distance_from_store_to_consumer	norm	4	0.4	km
contribution_to_the_purchase	norm	0.1	0.01	None (%)
capacity_of_one_box	unif	6	12	#
number_of_uses_of_one_box	unif	50	500	#
water_per_bottle	unif	0.5	2.5	L/bottle
electricity_per_bottle	norm	0.01	0.001	kWh/bottle
soda_per_bottle	norm	0.008	0.0008	kg/bottle
number_of_uses_pallet	norm	28	0.28	#
mass_divider	norm	1.2	0.12	kg
number_divider_per_pallet	norm	20	0.0001	#
number_of_uses_divider	norm	1	0.1	#

[1] First bound represents respectively mean and lower bound for normal (norm) and uniform (unif) distributions. Second bound represents respectively standard deviation and upper bounds for normal (norm) and uniform (unif) distributions.

- Transportation from store to consumers: consumer behaviour plays a significant role at this stage, limiting the potential for direct stakeholder intervention. However, since the impacts are related to the proportion of the total purchase represented by the beverage it could be minimized by diversifying product offerings in stores or selecting, at the beginning, stores with wider product variety.

The contribution analysis of Sref-SU is provided in Supplementary Material 5 (https://doi.org/10.57745/LBOEGQ). It depicts generally similar results, with higher contribution of the bottles to the overall impacts. In the following, the sensitivity of the results will be tested on three parameters commonly investigated in the literature: number of uses of the bottles, bottle mass and distance from production to retail. Those parameters are directly linked to two hotspots identified in the contribution analysis: impacts associated with the bottles and transportation from the logistic hub to sale. However, other input parameters might also influence the results, as additional hotspots were identified. To comprehensively identify all key parameters and quantify the influence, a Global Sensitivity Analysis is subsequently performed.

3.2. Sensitivity and uncertainty analysis

3.2.1. One-at-a-time sensitivity analysis (OAT-SA)

3.2.1.1. Effect of the number of uses of the reusable bottles on the environmental impacts. As described in the Material and Methods section, the number of uses derives from both the return rate and the rejection rate. The latter has been fixed to 1% for the OAT-SA and various return

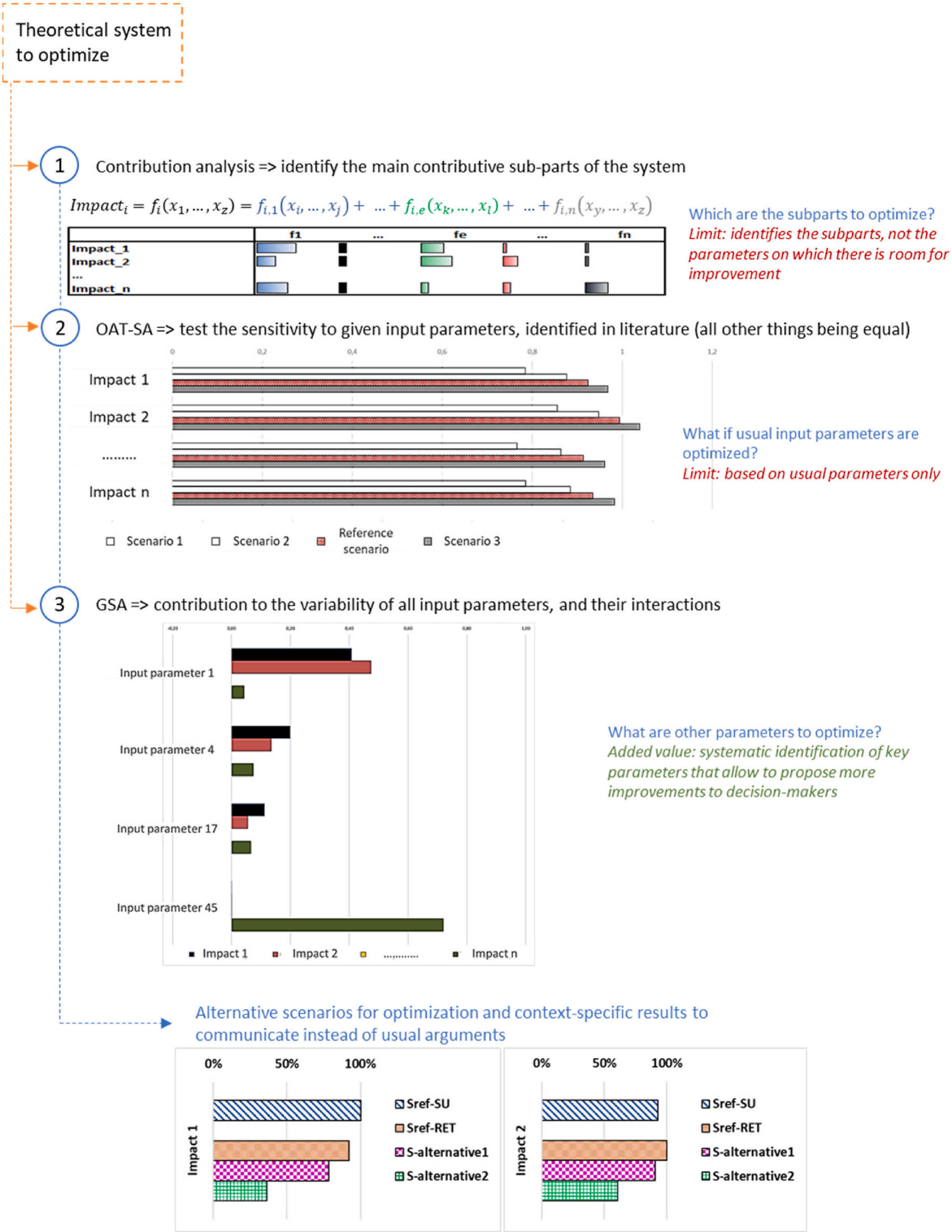


Fig. 2. Description of the different steps applied to identify key parameters to optimize to propose alternative scenarios.

rates were tested from 10% to 90%, to encompass the variability observed in (ADEME et al., 2018). The impacts of each sensitivity scenario are presented in Fig. 5, relative to Sref-SU, shown in blue and normalised to 1 for each impact category. Additionally, the impacts of Sref-RET (corresponding to a 66% return rate) are depicted in red.

Results demonstrate that a 50% return rate is not sufficient to achieve significantly lower impacts. A return rate of 70% with all other things held constant, achieves significantly lower impacts, especially on acidification (−22.8%), land use (−25.4%), and particulate matter (−18.7%). Increasing the return rate to the maximum tested value (90%) significantly reduces the impacts across all categories, ranging from −9.9% for human toxicity – cancer to −40% for acidification.

3.2.1.2. Effect of the mass of the bottles. As described in the Material and Methods section, the mass of the reusable bottles may be overestimated due to lack of technical data. To address this uncertainty, four

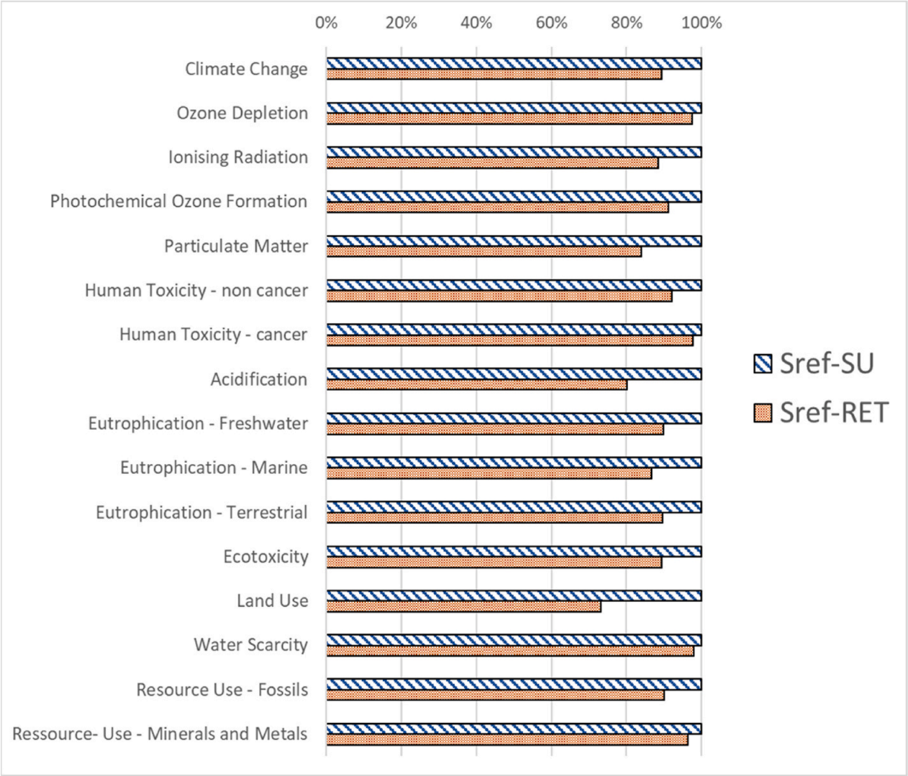


Fig. 3. Comparison of the reference scenario for single-use bottles (Sref-SU) and the reference scenario for reusable bottles (Sref-RET). For each impact category of EF3.0 method, the most impacting scenario has been set to 100% and the other scenario is represented relatively.

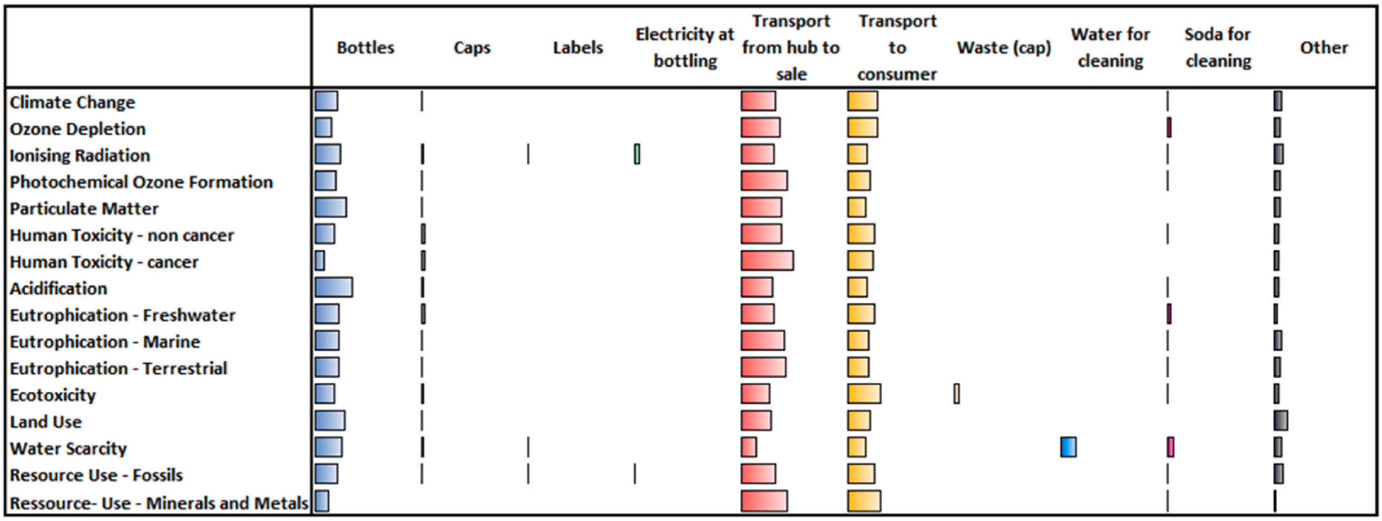


Fig. 4. contribution of the sub-parts to the studied environmental impacts for the reference system for reusable bottles. For each sub-part (in columns), the longer of the bar is proportional to the contribution to the impact category (in lines).

alternative bottle masses were considered, ranging from 400g/bottle to 850g/bottle in increments of 150g (Fig. 6).

Holding all other things constant, the results indicate a significant influence of bottle mass on the environmental impacts. Scenarios utilizing 400g and 550g bottles demonstrate lower impacts across all impact categories except water scarcity for Sref-mass-550. Sref-mass-400 exhibits lower impacts than Sref-SU, ranging from −12% (water scarcity) to −34.8% (acidification). Conversely, Sref-mass-850 is more impacting across all impact categories except for acidification, ranging from +3.9% (acidification) to +13.6% (water scarcity).

3.2.1.3. Effect of the distance from drink production to retail. The model does not explicitly include a parameter for the distance from production to retail. This is because the beverage undergoes and intermediate storage step at a logistic hub before being dispatched to retailers. Consequently, the sensitivity analysis focused on the distance between logistic hub and retail outlets. Considering a reference distance of 100 km, two alternatives were compared: 50 km and 150 km (Fig. 7).

Holding all other things constant, the results indicate a significant influence of the distance to sale on the environmental impacts. With a 50 km long distance, reusable bottles demonstrate lower impacts than single-use across all impact categories, ranging from −7.2% (water

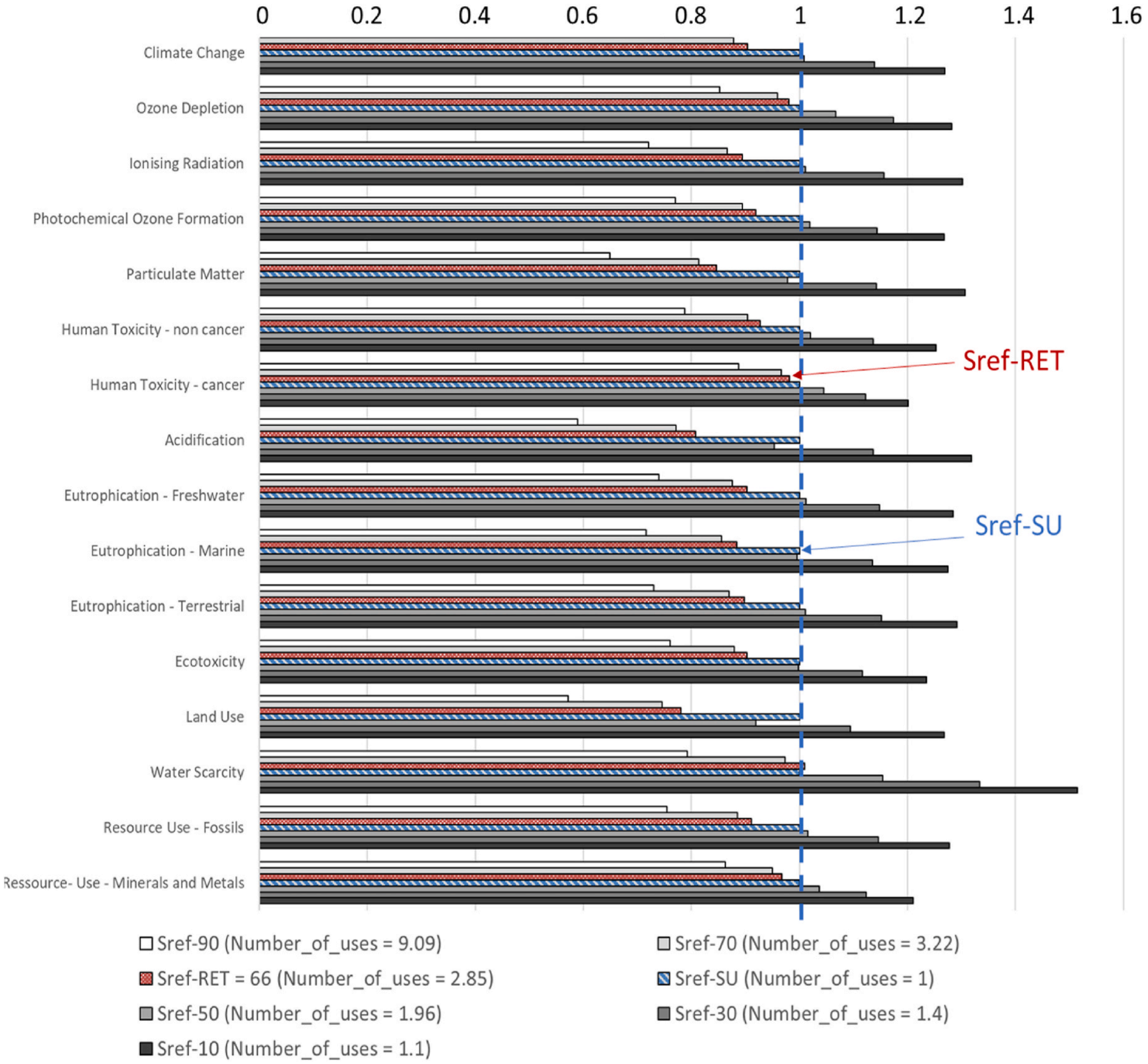


Fig. 5. Life Cycle Impact Assessment of Sref-SU compared to sensitivity scenarios on return rate. For each impact category, the impacts of each sensitivity scenarios are represented in the figure, relatively to Sref-SU, in blue, normalised to 1 for every impact category. The impacts of Sref-RET (corresponding to 66% return rate) are represented in red. The vertical blue bar is the value of Sref-SU for each impact category. Sref-XX is for Sref-RET with return rate = XX%, all other things being equal).

scarcity) to −32.3% (particulate matter). Conversely, with a 150 km long distance, reusable bottles are more impacting than single-use for 14 impact categories, ranging from +1.6% (particulate matter) to +23.9% (human toxicity – cancer).

3.2.2. *Uncertainty analysis*

Uncertainty analysis corroborates the primary results with small deviations from the Monte Carlo simulations' means for all assessed impact categories (Fig. 8), ranging from −12% (ozone depletion) to +2% (human toxicity – cancer). The exception is water scarcity (−36%), which can be attributed to the assumed water consumption of 0.5 L/bottle for cleaning (expert's estimation). This value represents the minimum value of the uniform distribution assigned to this parameter in the simulations, reflecting the lower bound identified in the literature.

3.2.3. *Global sensitivity analysis (GSA)*

For each impact category, the sum of first-order Sobol indices is close to 1, with a deviation of less than 10% (see Supplementary Material 7 (https://doi.org/10.57745/LBOEGQ)). This indicates that interactions between input parameters are minor and a first-order analysis is sufficient. Among the 55 input parameters, 10 contribute significantly (i.e. $S_i > 5\%$ for at least one impact category) to the variance of at least one impact category. Fig. 9 shows these 10 contributing parameters. Three input parameters have a high influence on almost all impact categories: distance from the logistic hub to the stores (S_i ranging from 4% for water scarcity to 65% for Human toxicity – cancer), bottle mass (S_i ranging from 7% for water scarcity to 31% for acidification) and return rate (S_i ranging from 6% for water scarcity to 24% for acidification).

Five input parameters exhibit a medium influence across most impact categories.

- Three primary – foreground – data: contribution to the purchase (i.e. share of the total purchase corresponding to the beverage), load of the transport modes, and distance from stores to consumers.
- Two background data: transport mode from hub to stores, and consumer transport mode.

Finally, two inputs parameters show high influence for only one impact category: type of material for the cap (for ozone depletion) and amount of water used to clean the bottles (for water scarcity).

3.3. *Comparison with alternative scenarios – optimization potentials*

Based on the contribution analysis and the sensitivity analyses, five

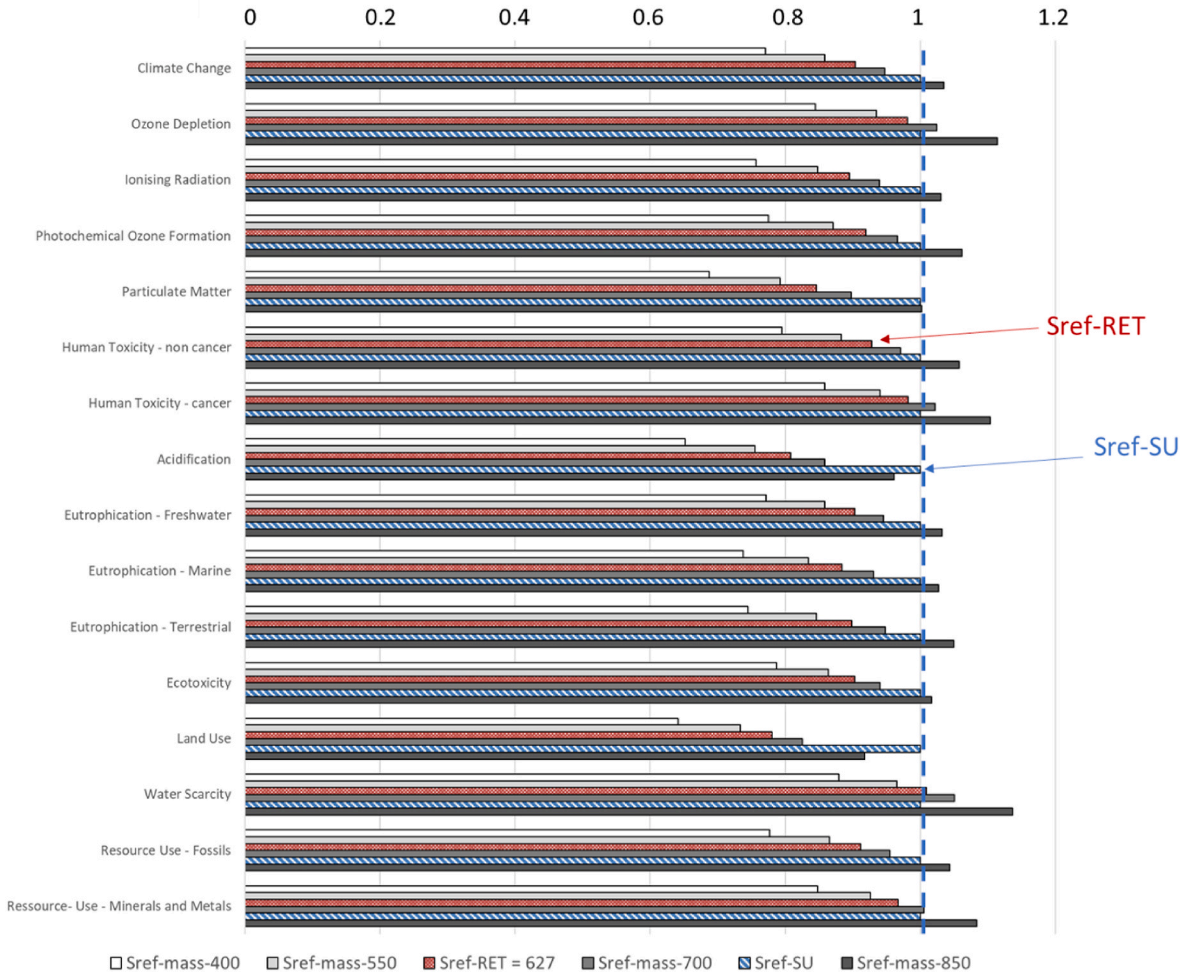


Fig. 6. Life Cycle Impact Assessment of Sref-SU compared to sensitivity scenarios on the mass of the bottles. For each impact category, the impacts of each sensitivity scenarios are represented in the figure, relatively to Sref-SU, in blue, normalised to 1 for every impact category. The impacts of Sref-RET (corresponding to 627g) are represented in red. The vertical blue bar is the value of Sref-SU for each impact category. Sref-mass-XX is for Sref-RET with mass of the bottles = XX g, all other things being equal).

alternative scenarios were established to assess the environmental impacts of different mitigation strategies (Table 6). Four scenarios, Sreturn, Smass, Spurchase and Slogistic respectively investigate: (i) the impact of improved return rate, (ii) the use of single-use bottles, (iii) optimizing consumer purchase (minimizing the beverage's contribution to the total basket) and (iv) optimizing logistical aspects. The last scenario is an optimized combination of the mitigation actions. A detailed description of the impacts on input parameters is provided in Table 6.

Fig. 10 presents comparative LCIA results between the two reference scenarios (Sref-SU and Sref-RET) and alternative scenarios. Each impact category is normalised, with the scenario having highest impact set to 100%. All other scenarios are expressed relative to this value. As detailed in the previous section, results show that Sref-RET offers relatively minor benefits compared to Sref-SU, with a maximum reduction of 18% observed for acidification. These benefits increase with alternative scenarios. Smass demonstrates modest improvements compared to Sref-RET, with around 10% less impacts across all impact categories. The potential benefits of using lighter bottles (reduced glass content per unit), identified though OAT-SA, are counterbalanced by the increased risk of breakage, which calculation is based on literature (Mata and Costa, 2001). Encouraging consumers to optimize their purchases through diversification of product offerings (Spurchase) could lead to impact reductions ranging from 9% to 17% depending on the impact category. Similarly, increasing the return rate could achieve reduction ranging from 7% up to 21%. Among the alternative scenarios, optimizing logistics (Slogistics) emerges as the most efficient, with potential to decrease the impacts by 16%–45%. This scenario combines a reduction in transportation distance (identified in OAT-SA) with other measures (different transport mode and optimized load). This leads to significantly better results than focusing on distance reduction. Finally, a combined approach (Soptimized) would lead to drastic reductions across all impact categories, ranging from 39% to 72%. More details on numerical values are provided in Supplementary Material 6 (https://doi.org/10.57745/LBOEGQ).

A worst-case scenario for reusable bottles was also designed and compared to a worst-case scenario for single-use bottles (not to the reference one - Sref-SU - for fair comparison). Details of modifications are provided in Table 7 and supplementary material 6 (https://doi.org/10.57745/LBOEGQ).

Results, in Fig. 11, demonstrate, at first, that worst-case scenarios have much higher impacts than both reference scenarios for single-use and reusable bottles. Secondly, the comparison between worst-case scenarios demonstrate that the implementation of a strategy with reusable bottles tends to higher environmental impacts (around 5% for all impact categories, expect for water scarcity that increases from 27%).

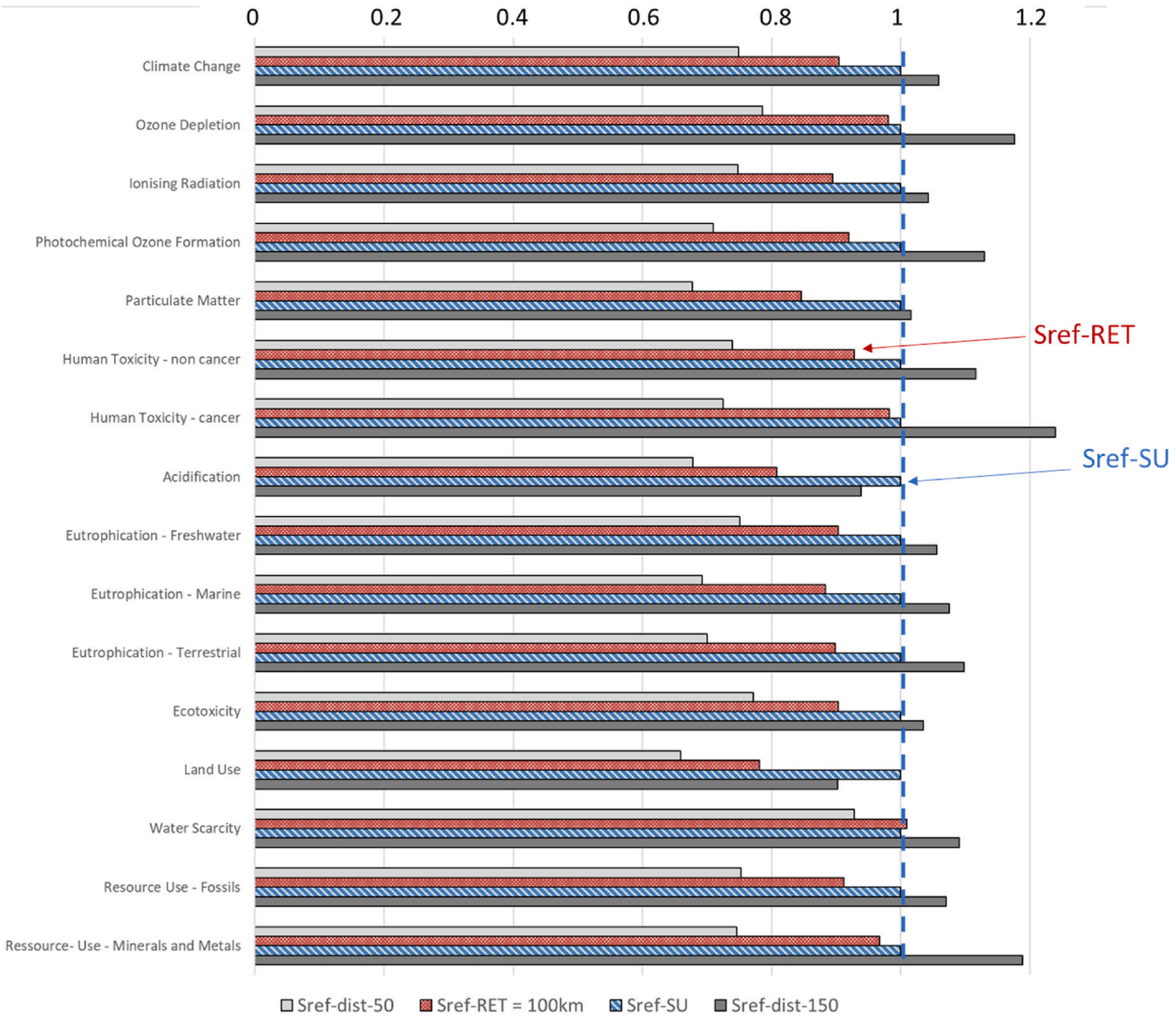


Fig. 7. Life Cycle Impact Assessment of Sref-SU compared to sensitivity scenarios on the distance from logistic hub to retail. For each impact category, the impacts of each sensitivity scenarios are represented in the figure, relatively to Sref-SU, in blue, normalised to 1 for every impact category. The impacts of Sref-RET (corresponding to 100 km) are represented in red. The vertical blue bar is the value of Sref-SU for each impact category. Sref-dist-XX is for Sref-RET with distance = XX km, all other things being equal).

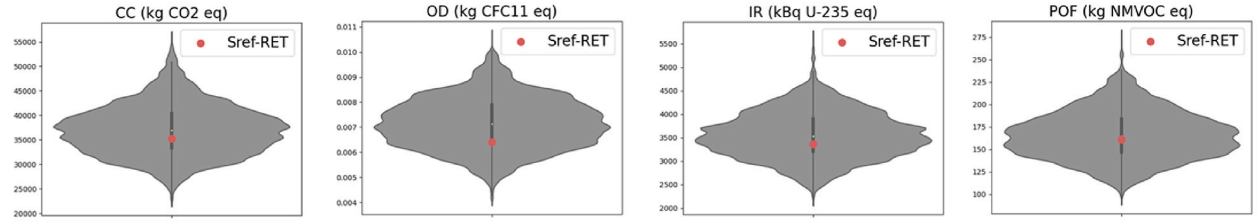
4. Discussion and perspectives

4.1. *Considering more context-specific key parameters to optimize reusable strategies*

4.1.1. *Key parameters: literature versus reality*

Given the time gap between the present study and the projected real-world within the FAIRCHAIN project, two initial scenarios (Sref-SU and Sref-RET) were designed to assess the potential environmental benefits of a reusable bottle strategy for the developed innovation. These scenarios were based on initial project hypotheses (for instance, the stores are those identified for consumer studies). However, the similarity of these scenarios with a real-world implementation remains highly hypothetical due to inherent uncertainties at this stage (for instance, the location of the stores where the beverage will be effectively sold could be different). The definition of scenarios is based on the future first implementation phase of the drink under study. There would be probable changes in the case of an upscaled production (for example, secondary packaging used for delivery and collect should be large metal carts instead of plastic boxes if mutualization with other products is implemented). In the future, more data should be included for a more comprehensive LCA in the case of the publication of the environmental impacts of the drink under study. The LCA results from these initial reference scenarios suggest minimal environmental benefits associated with reusable bottles. Worse, in the case of not-optimized systems (Sworst-RET), LCA indicates a slight increase in environmental impacts compared to single-use (Sworst-SU). These results differ from existing literature (ADEME et al., 2018), which often relies on idealized generic situations. This discrepancy could potentially lead to ineffective decision-making.

Without re-evaluate the interest of reusable bottles, the results argue for working on the optimization of the implementation scenarios within the project. To do so, the identification on key parameters for the system is necessary, and was performed through GSA in the present study. In addition to the three commonly considered influential parameters (i.e., return rate, bottle mass and distance to retail), seven influential parameters were identified: distance from sale to consumer, contribution to the purchase, transport load ratio, transport modes (especially for consumers and for the beverage from logistic hub to sale), cap material and amount of water used for bottle cleaning. These parameters are crucial for proposing efficient alternative scenarios. This study demonstrates the potential of proposed alternative scenarios to effectively reduce environmental impacts within the project, potentially requiring additional actions, as improved communication to increase return rate (these actions are not debated in the present study). More largely, a scientifically robust evaluation of the environmental impacts is crucial

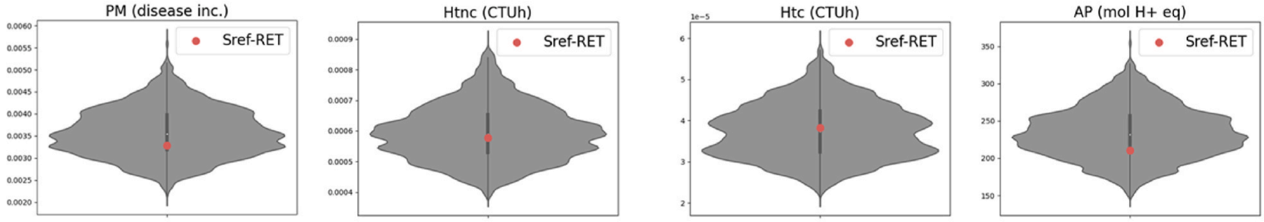


M	3.71E+04
SD	5.10E+03
CV	16.0%
Sref-RET	3.52E+04
V-ref/MC	-5%

M	7.16E-03
SD	1.01E-03
CV	16.3%
Sref-RET	6.40E-03
V-ref/MC	-12%

M	3.56E+03
SD	4.89E+02
CV	15.9%
Sref-RET	3.37E+03
V-ref/MC	-6%

M	1.66E+02
SD	2.66E+01
CV	19.1%
Sref-RET	1.61E+02
V-ref/MC	-3%

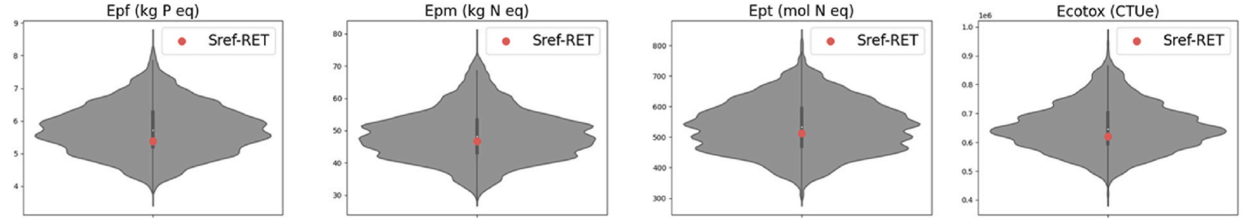


M	3.58E-03
SD	5.49E-04
CV	18.1%
Sref-RET	3.29E-03
V-ref/MC	-9%

M	5.95E-04
SD	8.91E-05
CV	17.6%
Sref-RET	5.77E-04
V-ref/MC	-3%

M	3.76E-05
SD	6.64E-06
CV	21.4%
Sref-RET	3.83E-05
V-ref/MC	2%

M	2.34E+02
SD	3.40E+01
CV	17.0%
Sref-RET	2.11E+02
V-ref/MC	-11%

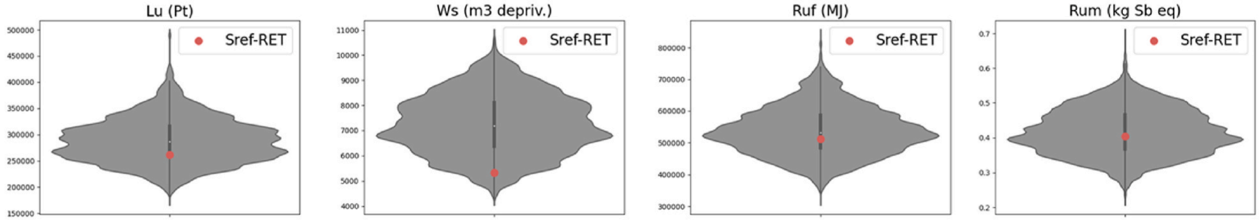


M	5.75E+00
SD	7.59E-01
CV	15.2%
Sref-RET	5.37E+00
V-ref/MC	-7%

M	4.86E+01
SD	7.69E+00
CV	18.8%
Sref-RET	4.68E+01
V-ref/MC	-4%

M	5.35E+02
SD	8.42E+01
CV	18.7%
Sref-RET	5.12E+02
V-ref/MC	-4%

M	6.52E+05
SD	8.19E+04
CV	14.4%
Sref-RET	6.21E+05
V-ref/MC	-5%



M	2.89E+05
SD	4.22E+04
CV	17.1%
Sref-RET	2.61E+05
V-ref/MC	-11%

M	7.24E+03
SD	1.18E+03
CV	19.5%
Sref-RET	5.33E+03
V-ref/MC	-36%

M	5.37E+05
SD	7.50E+04
CV	16.2%
Sref-RET	5.12E+05
V-ref/MC	-5%

M	4.18E-01
SD	6.55E-02
CV	18.6%
Sref-RET	4.05E-01
V-ref/MC	-3%

Fig. 8. Violin graphs depicting, in grey, the distributions of the impacts from Monte Carlo simulations for each impact category of EF3.0 (Functional Unit: "deliver 40,000 L of drink to the consumer". For each impact category, the results for Sref-RET is displayed as a red dot. Each figure is associated to a table in which, in the three first rows are indicated: Means (M), Standard Deviations (SD) and Coefficients of Variation (CV) of the environmental impacts from Monte Carlo (MC) simulations. For each impact category, the value of Sref-RET is indicated, as well as its variation from the Mean of MC simulations (V-ref/MC). Results of the simulations are available in supplementary material 4.

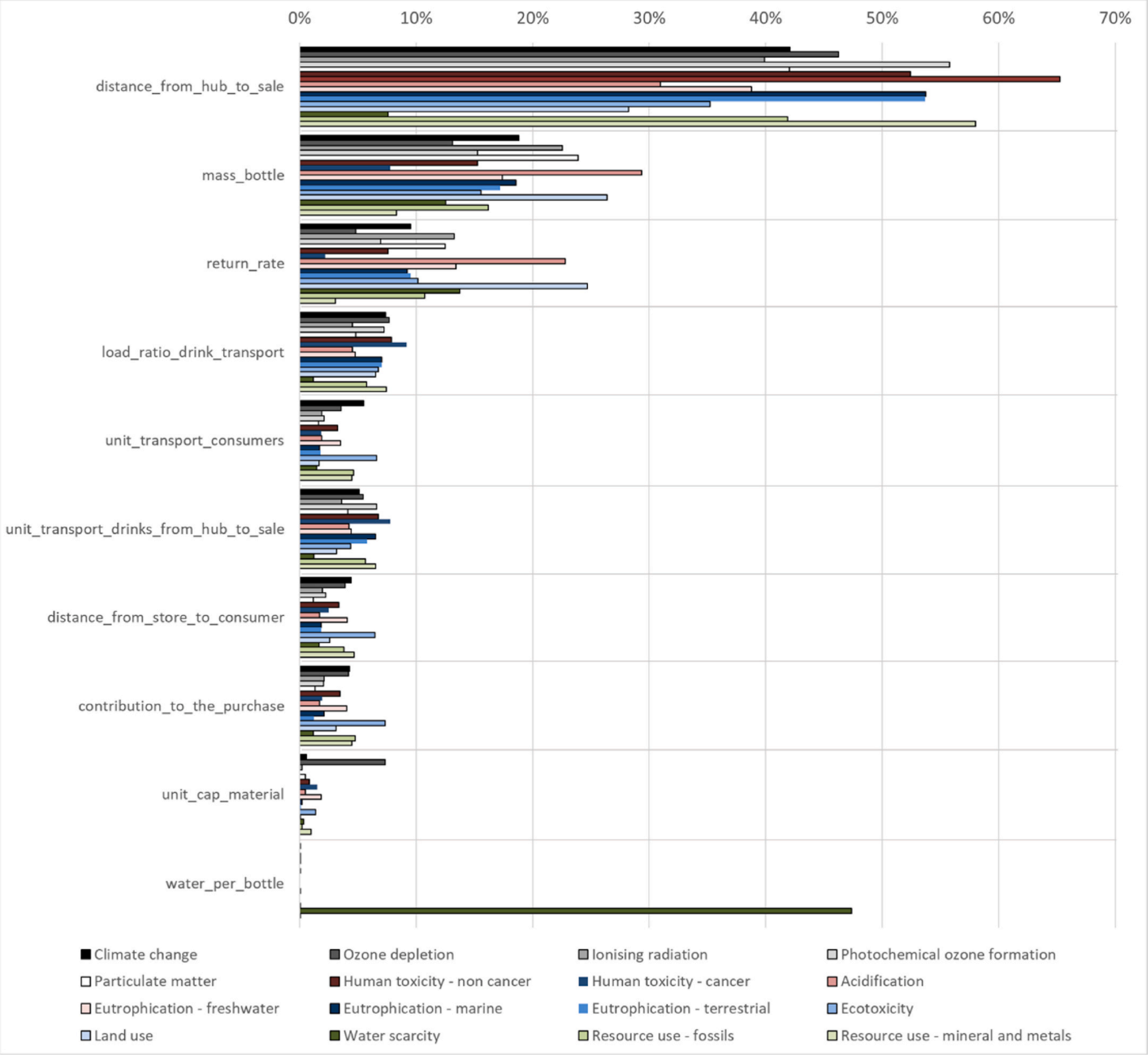


Fig. 9. Contribution of input parameters to the variance of the environmental impacts for all impact categories from EF3.0 method. Among the 55 input parameters, the first-order Sobol indexes of a given parameter are represented only if the parameter contributes to more than 5% of the variance for at least one impact category. All Sobol indices are available in supplementary material 4.

for developing relevant strategies for reusable bottles to end up with single-use packaging, and furthermore plastics (supposing future improvement to characterise the impacts of plastics with LCA). As regulations increasingly aim to phase out plastics, the need for credible alternatives become even more pressing.

4.1.2. *Key parameters: are they the same for all reusable bottle systems?*

While the proposed actions offer environmental potential benefits, their applicability may be limited to specific systems. The current GSA relies on our case study, and its results are, therefore, primarily valid for this context. As the first example, in catering services where return rate is already almost 100% (ADEME et al., 2018), room to improve environmental footprint is elsewhere. As the second example, the present study considers an individual stock of bottles, where the producer can only reuse bottles returned by their own consumers. However, reusable systems are more and more involve a higher degree of mutualization where any producer can potentially utilize bottles collected by a third part (depending on bottle type). In such systems, while the individual return rate remains probably influential, the capacity of the third part to procure returned bottles anyway should also be considered. This would modify the form of the equations to assess LCA impacts. This could not be assessed within the present model. To ensure and potentially enhance the environmental benefits of reusable bottle systems, it is recommended to replicate the GSA for each new application. Relying solely on a limited set of parameters, as common practice in many Life Cycle Assessments (LCA) studies, may be insufficient in certain cases. Therefore, a systematic study of the key parameters should be conducted. A significant challenge in applying GSA is defining appropriate values and distributions for model's input parameters. In this study, we principally employed expert's data, collected through interviews. The experts were both project-involved and external, all located in France. Through methods such as meta-analysis of literature and/or multiple expert's consultations, the parameter distributions could likely be further refined. Conversely, they could also become too generic to help with the eco-design of a system within a specific project. It is probable that these distributions will vary depending on the context, supporting the necessity to replicate GSA. However, this raises the question of the complexity related to the practice of LCA and to the incapacity of stakeholders to systematically provide contextualized results without being helped.

Table 6
Description of the alternative scenarios.

System	Description	Main input parameters impacted
Sreturn	Similar to Sref-RET with return rate improved from 66% to 85%	- Return rate: 85% instead of 66% for Sref-RET
Smass	Lighter bottles that imply more rejections at collection (more breakable)	- Mass of the bottle: 390 g instead of 627 g for Sref-RET - Rejected rate from collection: 15% instead of 1% for Sref-RET (based on breakability from (Mata and Costa, 2001))
Spurchase	Similar to Sref-RET with optimized purchase	- Contribution to the purchase: 5% instead of 10% for Sref-RET
Slogistic	Similar to Sref-RET with shorter distances from hub to stores, alternative transport modes and higher load ratio	- Distance from hub to stores: 50 km instead of 100 km for Sref-RET - Transports made with a 19t lorry - Load ratio of 1.2 (instead of 1)
Soptimized	Combination of Sreturn, Smass, Spurchase and Slogistic	- Return rate: 85% instead of 66% for Sref-RET - Contribution to the purchase: 5% instead of 10% for Sref-RET - Distance from hub to stores: 50 km instead of 100 km for Sref-RET - Transports made with a 19t lorry - Load ratio of 1.2 (instead of 1) - Mass of the bottle: 390 g instead of 627 g for Sref-RET - Rejected rate from collection: 4% instead of 1% for Sref-RET

Table 7
Description of the worst-case scenarios for single-use and, reusable bottles.

System	Description	Main input parameters impacted
Sworst-SU	Same modifications than Sworst-RET (for fair comparison)	- Longer distances compared to Sref-SU, for all distances (see details in supplementary material 2) - Load ratio of 0.8 (instead of 1) - Contribution to purchase is 0.25 (instead of 0.1) - Water per bottle for cleaning is 1.5L (instead of 0.5L)
Sworst-RET	Not optimized scenario	- Longer distances compared to Sref-SU - Load ratio of 0.8 (instead of 1) - Contribution to purchase is 0.25 (instead of 0.1) - Water per bottle for cleaning is 1.5L (instead of 0.5L) - Mass is still 627g but rejected rate is 15% (instead of 1%) - Return rate is 45%

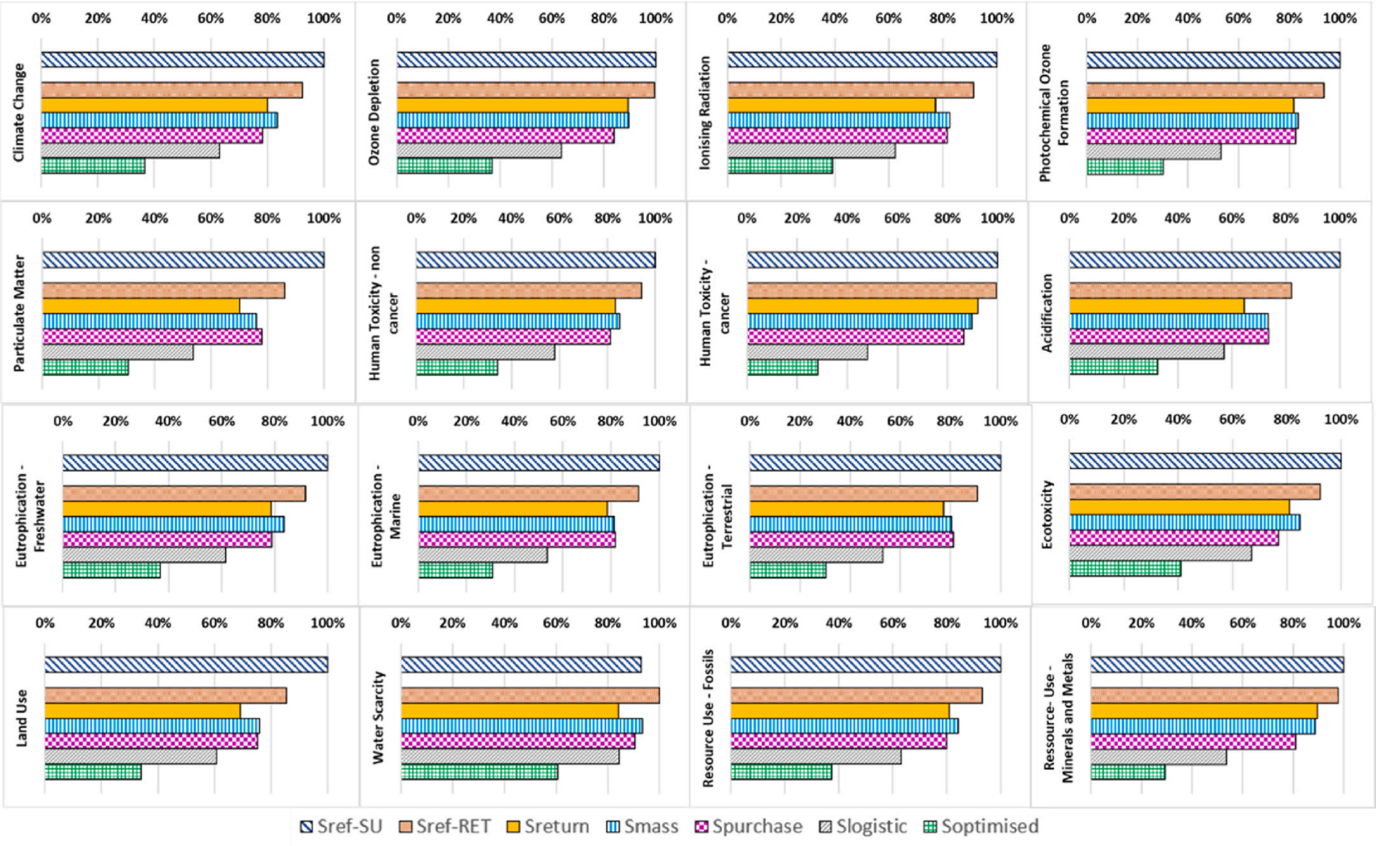


Fig. 10. Life Cycle Impact Assessment of Sref compared to alternative scenarios. For each impact category, the most impacting scenario is set to 100%. Other scenarios are expressed relatively.

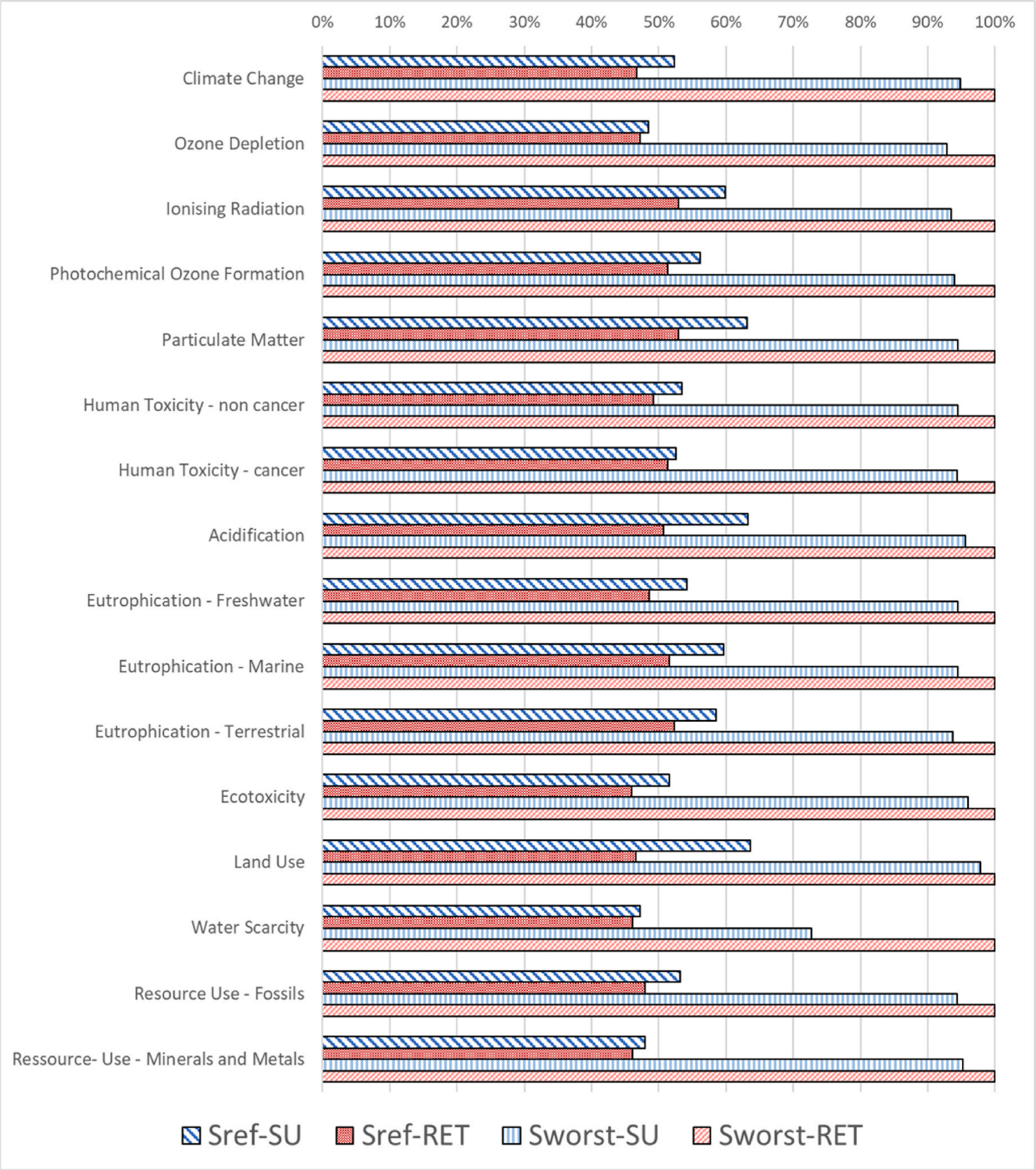


Fig. 11. Comparison of the worst-case scenario for single-use bottles (Sworst-SU) and the worst-case scenario for reusable bottles (Sworst-RET), with Sref-SU and Sref-RET. For each impact category of EF3.0 method, the most impacting scenario has been set to 100% and the other scenario is represented relatively.

4.2. More context-specific evaluations should not freeze projects

The scientific community recognizes the need to simplify LCA to enhance its ease of use for decision-making (Arzoumanidis et al., 2017). However, simplifying LCA complexity can also lead to controversial results or interpretations (Hunt et al., 1998). Therefore, it is crucial to strike a balance between simplified use and scientific robustness. In recent years, various methodological developments based on numerical approaches have been proposed, including simplified parametrized models based on GSA (Padey et al., 2013), multi-linear regressions (Pascual et al., 2015), and data mining (Sundaravaradan et al., 2011). The next step of the present work could be the development of simplified parametrized models as it was done since the 2010s, mainly for electricity production systems (Padey et al., 2013; Lacirignola et al., 2014; Douziech et al., 2021; Paulillo et al., 2022; Gibon and Hahn Menacho, 2023) as Sobol's indices were already calculated. These models rely on the reduction of the number of input parameters required to assess the potential environmental impacts. This should facilitate stakeholders' use and enable easier comparison of multiple scenarios. This method fosters a valuable trade-off between simplicity (simplified equation) and scientific robustness (statistical model).

Simplifying the practice of LCA can facilitate its adoption by stakeholders but this requires to develop a user-friendly interface that enables stakeholders to interact with the simplified LCA and make informed decisions based on the generated results. Looking ahead, a tool, specifically designed to assist small actors (SMEs, small producers, regional distributors) in developing reusable bottle strategies could be envisioned. This tool could offer two levels of complexity for casual and expert users. Casual users, lacking in-depth LCA knowledge, could leverage the tool to minimize the environmental impacts of their systems. Meanwhile, expert users would have the capability to apply GSA (being guided) to generate simplified models tailored to their specific contexts. In the example provided in the present paper, economic allocation was used to calculate the contribution of the drink to the impacts of the total basket. However, only a percentage is used as parameter in the GSA, giving user (especially expert) the possibility to use other allocation rules, depending on data availability in the future.

Additionally, a critical aspect of such tool would be the ability to present LCA results in diverse formats. Stakeholders, both within this project and across our broader network, have consistently highlighted the difficulty of translating LCA results in actionable decisions. While LCA adoption is increasing, its integration into the decision-making process remains limited, and often restricted to a few indicators (Subal et al., 2024), compromising its crucial multi-indicator perspective. Our analysis of arguments presented by companies developing reusable bottle strategies revealed a focus on three indicators: climate change, water use, and energy use. Project partners corroborate this preference, citing to key concerns: (i) the perceived difficulty in basing decisions on even three indicators and (ii) the lack of clarity surrounding the 16 indicators of EF3.0 method. To promote the utility of LCA results and facilitate effective decision-making, the tool should address this challenge through (1) exploring mathematical approaches to reduce the volume of information presented without compromising any environmental issue and (2) developing methods for presenting LCA results in a manner that is readily comprehensible for non-practitioners.

5. Conclusion

This study investigates the necessity of incorporating more context and specific details into LCA when developing implementation scenarios for reusable glass bottles. A theoretical case study is employed, acknowledging its inherent uncertainty due to its development nature (immaturity). We compare a reference scenario with reusable bottles to a reference scenario with single-use bottles. Results demonstrates that (1) the LCA results deviate significantly from common commercial arguments (detailed in introduction and supplementary materials 1), (2) reusable bottles remain a favourable option in comparison with single-use, and (3) their implementations require optimization considering both generic and specific constraints. To this end, we have complemented contribution analysis and the commonly used one-at-a-time analysis with a systematic exploration of input parameters influence though global sensitivity analysis. We propose alternative scenarios for testing, which exhibit promising environmental potentials. Looking ahead, we aim to establish the foundation for developing simplified parametrized models based on GSA. These models would be developed for various configurations to empower stakeholders to make informed decisions and develop scenarios simultaneously considering context-specific parameters.

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Link to dataset

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CRediT authorship contribution statement

Samuel Le Féon: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Geneviève Gésan-Guiziou:** Writing – review & editing, Validation, Project administration, Investigation, Funding acquisition. **Gwenola Yannou-Le Bris:** Writing – review & editing, Validation. **Joël Aubin:** Writing – review & editing, Validation. **Caroline Pénicaud:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Samuel Le Féon, for the authors.

Data availability

I have shared the link to my data

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Appendix A. Supplementary data

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