## Life Cycle Assessment of reusable and singleuse meal container systems

An evaluation of the resulting environmental impacts from food delivery and take-away systems with different configurations in Belgium and the Netherlands


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## Abbreviations guide

AL : Aluminium
ALCA : Attributional Life Cycle Assessment
AP : Acidification (potential)
BEP : Break-even point
cc : Cubic centimetres
CE : Circular Economy
CED : Cumulative energy demand
CFC : ChloroFluoroCarbon
CFF : Circular Footprint Formula
CLCA : Consequential Life Cycle Assessment
eBEP : Environmental break-even point
EoL : End-of-Life
EP : Eutrophication (potential)
eq : Equivalent
FU : Functional unit
g : Gram
GL : Glass
gsm : Grams per square meter
GW : Global warming
ILCD : International Reference Life Cycle Data System
ISO : International Organisation for Standardisation
KJ : Kilojoule
km : Kilometre
kWh : Kilowatt-hour
L : Litre
LCA : Life Cycle Assessment
LCC : Life Cycle Costing
LCI : Life Cycle Inventory
LCIA : Life Cycle Impact Assessment
MJ : Megajoule
OLD : Ozone layer depletion
p : Piece
PA : Paper
PEF : Product Environmental Footprint
PO : Photochemical oxidation
PP : Polypropylene
RR : Return rate
S-LCA : Social-Life Cycle Assessment
SOA : Secondary Organic Aerosol
SS : Stainless steel
tkm : Tonne-kilometre
VOC : Volatile Organic Compound
WU : Water use


#### Abstract

The use of single-use packaging has increased significantly over the past decades. Especially in the rapidly growing food delivery and take-away sector, single-use meal containers are eminently used. There are significant environmental burdens associated with this, mainly because of the depletion of the planet's natural resources and the pollution through waste generation. In line with the Circular Economy (CE) concept, in order to address these environmental consequences, reusable meal containers are being developed and introduced. Restaurants are considering replacing single-use with reusable containers. However, implementing reusable meal container systems can be realised in multiple ways because reusable containers need to be recollected and cleaned before they can be used again. Whether reusable packaging alternatives perform better environmentally than single-use ones needs to be evaluated.

This research used the Life Cycle Assessment (LCA) method to determine the environmental impacts of reusable and single-use meal container systems with different configurations. The impact categories Cumulative energy demand, Global warming, Ozone layer depletion, Photochemical oxidation, Acidification, Eutrophication and Water use were assessed. The obtained results were compared with each other to establish if reusable systems are environmentally preferred over single-use ones, and which configurations are required to realise this. This research analysed the product systems of three commonly used types of reusable meal boxes (from polypropylene, stainless steel and glass) and three commonly used types of single-use meal boxes (from polypropylene, aluminium and paper).

It can be concluded that reusable meal container systems are environmentally preferred over single-use ones, provided that correct (i.e. environmentally preferable) configurations are included in those systems. Nevertheless, when customers apply a cleaning method with high associated environmental impacts, or when the containers are retrieved with fossil fuel-based vehicles over long distances, the single-use systems can result in lower environmental impacts. The professional cleaning method of the containers also influences the resulting environmental impacts from reusable systems, although not as decisively as the customer cleaning method or the method for recollecting the containers. Additionally, it can be concluded that establishing reusable meal container systems with a high return rate is of utmost importance.

There is a high potential for reducing the environmental burdens associated with meal container systems by replacing single-use with reusable containers. Future research is required to obtain additional data for modelling the potential options for recollecting the containers and on how the return rates of these types of systems can be optimised in practice.


## Keywords

Packaging, Meal container, Reuse, Circular Economy (CE), Life Cycle Assessment (LCA), Environmental break-even point, Return rate

## Executive summary

Packaging is an important component of the food delivery and take-away sector. Packaging is required to deliver meals safely and hygienically to customers. The majority of the used meal containers in the food delivery and take-away sector is single-use. For instance, in the Netherlands alone, each year 876 million single-use meal containers are used in this sector. The use of single-use packaging goes accompanied by environmental impacts due to the depletion of the planet's natural resources (e.g. oil required for the production of plastics) and the pollution through waste generation. In line with the Circular Economy (CE) concept, in order to address these environmental consequences, reusable meal containers are being developed and introduced in this industry sector. Restaurants in Belgium and the Netherlands that want to improve their environmental footprints are considering the switch from singleuse to reusable meal containers. Several are currently already experimenting with this. The main difference between the delivery and take-away of meals packed in reusable or single-use meal containers is that the reusable containers need to be recollected from the customers and cleaned before a restaurant can use them again. There are different configurations possible for implementing reusable meal container systems, with different associated environmental impacts. This creates a barrier for restaurant owners to decide whether incorporating the switch from single-use to reusable containers would result in lower environmental impacts and what type of system configurations are required for realising this.

Recycling Netwerk Benelux is encouraging restaurants to start using reusable meal containers instead of single-use ones for their food delivery and take-away services. An Excel tool was developed to provide restaurant owners with insights into the environmental impacts resulting from delivery and takeaway systems for meals packed in reusable and single-use containers, and the different possible configurations. The aim of this research was to provide numerical input for the tool by performing Life Cycle Assessment (LCA) on these product systems and exporting the resulting environmental impacts to Excel.

## Methodology

In this research, LCA was used as the method for quantifying the environmental impacts resulting from delivery and take-away systems for meals packed in reusable and single-use containers with different configurations. LCA is nowadays a well-established method that can be used for determining the environmental impacts resulting from each of the life cycle stages of a product system. In order for the product systems to be comparable, the results were expressed according to the following functional unit: providing 43 meal delivery/take-away services with a 1.1 L volume meal container that can hygienically store food (containing liquid components). This implies that the impacts of a reusable meal container that is recollected and cleaned 43 times were compared with the impacts of 43 single-use containers. This research included the assessment of the environmental impact categories Cumulative energy demand, Global warming, Ozone layer depletion, Photochemical oxidation, Acidification, Eutrophication and Water use.

Key figure 1 provides an overview of the product systems of reusable and single-use meal containers. In this case, the Use stage of the life cycle of reusable meal containers consists of multiple components, which were assessed individually. This provided a clear overview of what parts of the environmental impacts result from the different processes, instead of the total impacts from the Use stage. The different possible system configurations for the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages that were identified and assessed during this research are also included in the figure.


Key figure 1: Flowcharts for a reusable and a single-use meal container system for food delivery and take-away.

## Results

Based on the most ordered types of meals in Belgium and the Netherlands, it was decided to only include meal boxes/bowls in this research because these types of meal containers are suitable for containing the majority of meal types. Three commonly used reusable boxes produced from different material types (polypropylene, stainless steel and glass) and three commonly used single-use boxes produced from different material types (polypropylene, aluminium and paper) were considered in this research. First, the resulting environmental impact from the possible system configurations for the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages of a reusable meal container system were assessed.


Key figure 2: Relative environmental impacts per impact category for four customer cleaning options.
Key figure 2 provides an overview of how the impacts from the customer cleaning methods compare with each other. None customer cleaning was not included in this figure, because there are no environmental impacts associated with this. The findings indicate that, from the other four options, cold water rinsing is the environmentally preferred option and handwashing results in the highest environmental impacts.

For the Retrieval and redistribution stage, hardly any data were available for the average transportation distances required for recollecting a reusable meal container and the vehicles used for this. This was thus modelled based on five scenarios considered in this research. Scenario 1a includes a retrieval round of 21.5 km to collect 43 containers with an electric bicycle. Scenario lb includes the same retrieval round, but with a scooter instead of an electric bicycle. Scenario 2a includes collecting 43 containers with a van from a drop-off point over a distance of 3.44 km . Scenario 2 b includes the same as scenario 2a, but over a distance of 1.72 km . Scenario 2c includes collecting 43 containers with an electric bicycle from a drop-off point over a distance of 8.19 km .


Key figure 3: Relative environmental impacts per impact category for the five retrieval and redistribution scenarios assessed in this research.

Key figure 3 provides an overview of how the impacts from the five retrieval and redistribution scenarios assessed in this research compare with each other. No scenario for at-home/at-restaurant exchanges was included in this figure, because it was expected that there are no additional transportation distances and associated environmental impacts required for this. The findings indicate that from the five scenarios, scenario 2 c is environmentally preferred. Scenario 1 b results in the highest environmental impacts for all impacts categories, except for the category Water use, where scenario 1a performs marginally worse. Especially for the impact category Photochemical oxidation, the resulting impacts from scenario 1 b are significantly higher than those from all other scenarios (at least 31 times higher). This can mainly be attributed to the formation of Secondary Organic Aerosols (SOA) that takes place during the incomplete fuel combustion of two-stroke scooters.


Key figure 4: Relative environmental impacts per impact category for each of the professional cleaning options.
Key figure 4 provides an overview of how the impacts from the professional cleaning methods compare with each other. The findings indicate that industrial dishwashing is the environmentally preferred option for all impact categories, except for Ozone layer depletion, where conventional dishwashing results in the lowest environmental impacts. For the other six impact categories, conventional dishwashing results in the highest environmental impacts. It is however important to take into account that additional transportation might be required for industrial dishwashing, although previous research indicated that, even with distances up to 50 km , this was still the environmentally preferred cleaning option.

From consulting with multiple organisations within the food delivery and take-away sector, the most realistic configurations for reusable meal container systems were identified. These are: cold water rinsing as the customer cleaning method, making use of at-home/at-restaurant exchanges for recollecting the containers and professional dishwashing as the professional cleaning method. Those configurations were included in the modelling of the complete life cycles of the reusable meal container systems. The resulting environmental impacts were assessed and compared with those from the complete life cycles of the single-use meal container systems.


Key figure 5: Relative environmental impacts per impact category for all meal boxes considered in this research.
Key figure 5 provides an overview of the resulting environmental impacts from the complete life cycles of the six meal boxes considered in this research. The findings indicate that all three reusable boxes result in lower impacts than all three single-use boxes for each of the seven impact categories. The reusable box from stainless steel results in the lowest environmental impacts (which can mainly be attributed to the high durability and recyclability of steel) and the single-use box from polypropylene in the highest for all impact categories. Significant differences in resulting environmental impacts can be observed for meal containers of different material types, both when comparing reusable boxes with each other and when comparing single-use boxes with each other.

Three sensitivity analyses were performed to check how the obtained results would be influenced by this. For each sensitivity analysis, one of the most realistic system configurations was altered to the worst-case option (i.e. resulting in the highest environmental impacts) for one of the life cycle stages Customer cleaning, Retrieval and redistribution, and Professional cleaning. The findings indicated that the customer cleaning method and the method for recollecting the containers are decisive in establishing reusable meal container systems that are environmentally preferred over single-use ones. When customers handwash the containers, only for the impact category Acidification all reusable boxes are still environmentally preferred over all single-use boxes. However, all reusable boxes result in higher environmental impacts for the impact categories Ozone layer depletion and Eutrophication than all single-use boxes. When the containers are recollected by making use of a retrieval round with a scooter, all reusable boxes result in higher environmental impacts for the impact categories Ozone layer depletion and Photochemical oxidation than all single-use boxes. Nevertheless, for the other five impact categories, the environmental impacts from the reusable boxes remain lower than those from the singleuse boxes. Additionally, the findings indicated that the professional cleaning method is also of importance, although the results did not change as drastically as when including the worst-case system configurations for the Customer cleaning and Retrieval and redistribution stages. For six out of the seven impact categories, the resulting environmental impacts increased, but all reusable meal container systems were still environmentally preferred over all single-use ones.

The final results section was dedicated to analysing the environmental break-even points and the importance of the return rate. Break-even point analysis was applied to determine after how many use cycles a certain reusable meal container system would be environmentally preferred if it would replace a certain single-use system. The findings indicated that, although most environmental break-even points are relatively low (e.g. they would be reached within the technical lifetime of the reusable meal containers), relatively high return rates are required to reach those break-even points in practice. The return rate can be described as the share of reusable meal containers that in practice gets returned to the restaurant. When taking the most realistic configurations for reusable meal container systems into account, a return rate of at least $92 \%$ would be required in order to reach the environmental break-even points for all impact categories.

## Conclusions

This research determined by using LCA how food delivery and take-away systems with reusable and single-use meal containers with different configurations compare with each other from an environmental life cycle perspective in Belgium and the Netherlands. It can be concluded that reusable meal container systems result in significantly lower environmental impacts than single-use systems for all seven impact categories assessed in this research, provided that correct (i.e. environmentally preferable) configurations are included in those systems. Moreover, establishing high return rates proves to be a key aspect for reusable meal container systems to be environmentally preferred over single-use systems in practice.

## Recommendations

Key figure 6 provides an overview of the most important influencing factors to the environmental impacts resulting from both reusable and single-use meal container systems. Recycling Netwerk Benelux is advised to emphasise the importance of these different factors accordingly to organisations within the food delivery and take-away sector in Belgium and the Netherlands. Clearly communicating towards customers to apply the correct cleaning method after use, implementing efficient systems for recollecting the containers and optimising the return rates of reusable systems have the highest priority.


Key figure 6: Overview of the degree of influencing factors to the environmental impacts resulting from reusable and single-use meal container systems.

## Managementsamenvatting (Executive summary in Dutch)

Verpakkingen zijn een belangrijk onderdeel van de markt voor afhaal- en bezorgmaaltijden. Verpakkingen zijn nodig om maaltijden veilig en hygiënisch bij klanten te bezorgen. Het merendeel van de gebruikte maaltijdverpakkingen in de afhaal- en bezorgmaaltijden sector bestaat uit wegwerpverpakkingen. Zo worden er in Nederland alleen al jaarlijks 876 miljoen wegwerpverpakkingen in deze sector gebruikt. Het gebruik van wegwerpverpakkingen gaat gepaard met milieudruk door het gebruik van natuurlijke grondstoffen (zoals de benodigde olie voor de productie van kunststoffen) en de generatie van afval. In lijn met het concept van de Circulaire Economie (CE) worden voor deze industriesector herbruikbare maaltijdverpakkingen ontwikkeld en geïntroduceerd om de bovengenoemde milieugevolgen aan te pakken. Restaurants in België en Nederland die hun ecologische voetafdruk willen verbeteren, overwegen de overstap van wegwerp naar herbruikbare maaltijdverpakkingen. Een aantal restaurants experimenteert hier momenteel al mee. Het belangrijkste verschil tussen bezorg- en afhaalsystemen van maaltijden in herbruikbare en wegwerpverpakkingen is dat de herbruikbare verpakkingen terug moeten worden verkregen van de klanten en dat ze moeten worden gereinigd voordat een restaurant ze opnieuw kan gebruiken. Er zijn verschillende systeemconfiguraties mogelijk voor het implementeren van herbruikbare maaltijdverpakkingssystemen, met verschillende bijbehorende milieudrukken. Hierdoor is het voor restauranteigenaren lastig is om te beslissen of de overstap van wegwerp naar herbruikbare maaltijdverpakkingen daadwerkelijk leidt tot een lagere milieudruk en welke systeemconfiguraties nodig zijn om dit te realiseren.

Recycling Netwerk Benelux moedigt restaurants aan om herbruikbare in plaats van wegwerp maaltijdverpakkingen te gaan gebruiken voor hun maaltijdbezorging- en afhaaldiensten. Er is een Excel tool ontwikkeld om restauranteigenaren inzicht te geven in de milieudruk van afhaal- en bezorgsystemen voor maaltijden verpakt in herbruikbare en wegwerpverpakkingen met verschillende mogelijke systeemconfiguraties. Het doel van dit onderzoek was om de cijfermatige basis te leveren voor de tool door middel van levenscyclusanalyse (LCA) van deze productsystemen en het exporteren van de resulterende milieudrukken naar Excel.

## Methodologie

In dit onderzoek is LCA als methode gebruikt voor het kwantificeren van de milieudrukken van afhaalen bezorgsystemen voor maaltijden verpakt in herbruikbare en wegwerpverpakkingen met verschillende systeemconfiguraties. LCA is tegenwoordig een gevestigde methode die kan worden gebruikt voor het bepalen van de milieudrukken in elk van de levenscyclusfasen van een productsysteem. Om de productsystemen vergelijkbaar te maken, zijn de resultaten uitgedrukt per zogenoemde functionele eenheid. Deze was: 43 maaltijdbezorging/afhaaldiensten met een $1,1 \mathrm{~L}$ volume maaltijdverpakking waarin voedsel (met vloeibare componenten) hygiënisch kan worden vervoerd. Dit houdt in dat de milieudrukken van een herbruikbare maaltijdverpakking die 43 keer wordt opgehaald en gereinigd werden vergeleken met de milieudrukken van 43 wegwerpverpakkingen. Dit onderzoek omvatte de beoordeling van de volgende milieudruk categorieën: Cumulative energy demand, Global warming, Ozone layer depletion, Photochemical oxidation, Acidification, Eutrophication en Water use.

Het Engelstalige Kernfiguur 1 geeft een overzicht van de productsystemen van herbruikbare en wegwerp maaltijdverpakkingen. In dit geval bestaat de gebruiksfase van de levenscyclus van herbruikbare maaltijdverpakkingen uit meerdere componenten. Deze zijn afzonderlijk beoordeeld om inzicht te geven in welke milieudrukken het gevolg zijn van de verschillende processen in de gebruiksfase. Tijdens dit onderzoek zijn er verschillende mogelijke systeemconfiguraties voor de levenscyclusfasen reinigen door de klant, ophalen en herdistributie, en professioneel reinigen vastgesteld en geanalyseerd. Deze zijn ook opgenomen in de figuur.


Kernfiguur 1: Stroomdiagrammen voor een herbruikbaar en een wegwerp maaltijdverpakkingssysteem voor het afhalen en bezorgen van maaltijden.

## Resultaten

Op basis van de meest bestelde soorten maaltijden in België en Nederland is besloten om alleen maaltijdbakken/-kommen in dit onderzoek op te nemen, omdat deze geschikt zijn voor het verpakken van de meeste maaltijdsoorten. In dit onderzoek is gekeken naar drie veelgebruikte herbruikbare bakken gemaakt van verschillende materiaalsoorten (polypropyleen, roestvrij staal en glas) en drie veelgebruikte wegwerp bakken gemaakt van verschillende materiaalsoorten (polypropyleen, aluminium en papier). De resulterende milieudrukken van de verschillende systeemconfiguraties voor de levenscyclusfasen reinigen door de klant, ophalen en herdistributie, en professioneel reinigen zijn eerst geanalyseerd en beoordeeld.


Kernfiguur 2: Relatieve milieudrukken per milieudruk categorie voor vier opties voor de levenscyclusfase reinigen door de klant.

Kernfiguur 2 geeft een overzicht van hoe de milieudrukken van de verschillende reinigingsmethoden door de klant zich tot elkaar verhouden. De optie geen reiniging door de klant is niet opgenomen in de figuur, omdat hier geen milieudrukken aan verbonden zijn. De resultaten laten zien dat, van de vier opties, schoonspoelen met koud water de meest milieuvriendelijke optie is en met de hand afwassen de hoogste milieudrukken veroorzaakt.

Voor de levenscyclusfase ophalen en herdistributie waren er nauwelijks gegevens beschikbaar over de gemiddelde afstanden die moeten worden afgelegd om een herbruikbare maaltijdverpakking terug te verkrijgen en de daarvoor gebruikte transportvoertuigen. Dit is daarom gemodelleerd op basis van vijf scenario's. Scenario 1a omvat een ophaalronde van $21,5 \mathrm{~km}$ om 43 verpakkingen op te halen met een elektrische fiets. Scenario 1b omvat dezelfde ophaalronde, maar met een scooter in plaats van een elektrische fiets. Scenario 2 a omvat het ophalen van 43 containers met een bestelwagen van een inleverpunt over een afstand van $3,44 \mathrm{~km}$. Scenario 2 b omvat hetzelfde als scenario 2 a , maar dan over een afstand van $1,72 \mathrm{~km}$. Scenario 2 c omvat het ophalen van 43 containers met een elektrische fiets van een inleverpunt over een afstand van $8,19 \mathrm{~km}$.


Kernfiguur 3: Relatieve milieudrukken per milieudruk categorie voor de vijf in dit onderzoek opgenomen scenario's voor de levenscyclusfase ophalen en herdistributie.

Kernfiguur 3 geeft een overzicht van hoe de milieudrukken van de vijf in dit onderzoek opgenomen scenario's voor de levenscyclusfase ophalen en herdistributie zich tot elkaar verhouden. In de figuur is geen scenario voor uitwisselingen bij de klant thuis/bij het restaurant opgenomen, omdat verwacht werd dat hiervoor geen extra transportafstanden en bijbehorende milieudrukken nodig zijn. De resultaten tonen aan dat, van de vijf scenario's, scenario 2c vanuit milieuoogpunt de voorkeur heeft. Scenario 1b resulteert in de hoogste milieudrukken voor alle milieudruk categorieën, behalve voor de categorie Water use, waar scenario 1a nog enigszins slechter presteert. Vooral voor de milieudruk categorie Photochemical oxidation is de resulterende milieudruk van scenario 1b significant hoger dan die van alle andere scenario's (ten minste 31 keer zo hoog). Dit kan voornamelijk worden toegeschreven aan de vorming van secundaire organische aerosolen (Secondary Organic Aerosols, SOA) die plaatsvindt tijdens de onvolledige brandstofverbranding van tweetakt scooters.


Kernfiguur 4: Relatieve milieudrukken per milieudruk categorie voor de opties voor de levenscyclusfase professioneel reinigen.

Kernfiguur 4 geeft een overzicht van hoe de mileudrukken van de professionele reinigingsmethoden zich tot elkaar verhouden. De resultaten laten zien dat industrieel vaatwassen de meest milieuvriendelijke optie is voor alle milieudruk categorieën, behalve voor Ozone layer depletion, waar conventioneel vaatwassen resulteert in de laagste milieudruk. Voor de overige zes milieudruk categorieën resulteert conventioneel vaatwassen in de hoogste milieudrukken. Het is echter belangrijk om rekening te houden met mogelijk extra transport voor industrieel vaatwassen, alhoewel eerder onderzoek aantoonde dat dit, zelfs bij afstanden tot 50 km , nog steeds de meest milieuvriendelijke reinigingsoptie was.

Uit overleg met meerdere organisaties binnen de afhaal- en bezorgmaaltijden sector zijn de meest realistische systeemconfiguraties voor herbruikbare maaltijdverpakkingssystemen vastgesteld. Dit zijn: schoonspoelen met koud water als reinigingsmethode door de klant, het gebruik maken van uitwisselingen bij de klant thuis/bij het restaurant voor het terug verkrijgen van de verpakkingen en professioneel vaatwassen als de professionele reinigingsmethode. Deze systeemconfiguraties zijn opgenomen in het modelleren van de volledige levenscycli van de herbruikbare maaltijdverpakkingssystemen. De resulterende milieudrukken zijn beoordeeld en vergeleken met die van de volledige levenscycli van de wegwerp maaltijdverpakkingssystemen.


Kernfiguur 5: Relatieve milieudrukken per milieudruk categorie voor alle maaltijdbakken die in dit onderzoek zijn onderzocht.

Kernfiguur 5 geeft een overzicht van de resulterende milieudrukken van de volledige levenscycli van de zes maaltijdbakken die in dit onderzoek zijn onderzocht. De resultaten tonen aan dat alle drie de herbruikbare bakken resulteren in lagere milieudrukken dan alle drie de wegwerp bakken voor elk van de zeven milieudruk categorieën. De herbruikbare bak van roestvrij staal resulteert in de laagste milieudrukken (wat vooral kan worden toegeschreven aan de hoge levensduur en recycleerbaarheid van staal) en de wegwerp bak van polypropyleen resulteert in de hoogste milieudrukken voor alle milieudruk categorieën. Zowel bij het vergelijken van herbruikbare bakken onderling als bij het vergelijken van wegwerp bakken onderling kunnen significante verschillen in resulterende milieudrukken worden waargenomen voor maaltijdverpakkingen van verschillende materiaalsoorten.

Er zijn drie gevoeligheidsanalyses uitgevoerd om na te gaan hoe de verkregen resultaten hierdoor zouden worden beïnvloed. Voor elke gevoeligheidsanalyse werd één van de meest realistische systeemconfiguraties gewijzigd naar de optie die resulteert in de hoogste milieudrukken voor éen van de levenscyclusfasen reinigen door de klant, ophalen en herdistributie, en professioneel reinigen. De resultaten toonden aan dat de reinigingsmethode die door de klant wordt toegepast en de methode voor het terug verkrijgen van de verpakkingen bepalend zijn in het realiseren van herbruikbare maaltijdverpakkingssystemen die milieuvriendelijker zijn dan wegwerp systemen. Wanneer klanten de verpakkingen met de hand afwassen, hebben alleen voor de milieudruk categorie Acidification alle herbruikbare systemen nog steeds de voorkeur boven alle wegwerp systemen. Alle herbruikbare systemen resulteren echter in hogere milieudrukken voor de milieudruk categorieën Ozone layer depletion en Eutrofication dan alle wegwerp systemen. Wanneer de verpakkingen worden opgehaald door een ophaalronde met een scooter, resulteren alle herbruikbare systemen in hogere milieudrukken voor de milieudruk categorieën Ozone layer depletion en Photochemical oxidation dan alle wegwerp systemen. Echter, voor de andere vijf milieudruk categorieën blijven de milieudrukken van herbruikbare systemen lager dan die van wegwerp systemen. Daarnaast toonden de resultaten aan dat de professionele reinigingsmethode ook van belang is. De resultaten veranderen echter niet zo drastisch als bij het opnemen van de systeemconfiguraties die in de hoogste milieudrukken resulteren voor de levenscyclusfasen reinigen door de klant en ophalen en herdistributie. Voor zes van de zeven milieudruk
categorieën namen de resulterende milieudrukken toe, maar alle herbruikbare maaltijdverpakkingssystemen hadden nog steeds de voorkeur boven alle wegwerp systemen.

De laatste sectie van het resultatenhoofdstuk is gewijd aan het analyseren van de milieudruk omslagpunten en het belang van het retourpercentage. De analyse van de omslagpunten werd toegepast om te bepalen na hoeveel gebruikscycli een herbruikbaar maaltijdverpakkingssysteem zou resulteren in lagere milieudrukken wanneer het een wegwerp systeem zou vervangen. De resultaten toonden aan dat de meeste omslagpunten relatief laag liggen (deze zouden worden bereikt binnen de technische levensduur van de herbruikbare maaltijdverpakkingen), maar er relatief hoge retourpercentages nodig zijn om dat aantal gebruikscycli in de praktijk te bereiken. Het retourpercentage kan worden beschreven als het aandeel herbruikbare maaltijdverpakkingen dat in de praktijk weer bij het restaurant terug komt. Wanneer rekening wordt gehouden met de meest realistische configuraties voor herbruikbare maaltijdverpakkingssystemen, zou een retourpercentage van ten minste $92 \%$ nodig zijn om de milieudruk omslagpunten voor alle milieudruk categorieën te bereiken.

## Conclusies

Dit onderzoek heeft aan de hand van LCA vastgesteld hoe maaltijdbezorging- en afhaalsystemen met herbruikbare en wegwerpverpakkingen met verschillende systeemconfiguraties zich vanuit milieuoogpunt tot elkaar verhouden in België en Nederland. Geconcludeerd kan worden dat herbruikbare maaltijdverpakkingssystemen resulteren in significant lagere milieudrukken dan wegwerp systemen voor alle zeven in dit onderzoek geanalyseerde milieudruk categorieën. Hiervoor is het echter wel van belang dat correcte (milieuvriendelijke) systeemconfiguraties worden opgenomen in de herbruikbare systemen. Daarnaast blijkt het realiseren van hoge retourpercentages een essentieel aspect te zijn om er in de praktijk voor te zorgen dat herbruikbare maaltijdverpakkingssystemen resulteren in lagere milieudrukken dan wegwerp systemen.

## Aanbevelingen

Kernfiguur 6 geeft een overzicht van de belangrijkste factoren die van invloed zijn op de milieudrukken van zowel herbruikbare als wegwerp maaltijdverpakkingssystemen. Recycling Netwerk Benelux wordt geadviseerd om het belang van deze verschillende factoren dienovereenkomstig te benadrukken richting organisaties in de afhaal- en bezorgmaaltijden sector in België en Nederland. Duidelijk communiceren naar klanten over het toepassen van de correcte reinigingsmethode na gebruik, het implementeren van efficiënte systemen voor het terug verkrijgen van de verpakkingen en het optimaliseren van de retourpercentages van herbruikbare systemen hebben de hoogste prioriteit.


Kernfiguur 6: Overzicht van de mate van beïnvloedende factoren op de milieudruk van herbruikbare en wegwerp maaltijdverpakkingssystemen.

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## 1. Introduction

The use of packaging has increased significantly due to a combination of global population growth, increased consumer demand, and an increase in global trade systems (Pongrácz, 2007; Twede, 2016). Production and consumption of goods increasingly occur at different parts of the world and at different times. Therefore, the produced goods often have to be transported and distributed across the world. Packaging serves as a connecting link between production and consumption, enabling the spread between these phases over long distances and timespans (Pongrácz, 2007).

Packaging is especially relevant and important for the food industry (Pongrácz, 2007; Qasim et al., 2020; Silayoi, \& Speece, 2007). Packaging helps to extend the food's shelf life, enables its safe and hygienic delivery, protects it from any damage during distribution and storage, and can communicate essential information (e.g. nutritional) to customers (Qasim et al., 2020). Moreover, by using packaging, the quantities of food provided can be tuned to changing consumption patterns, with the aim to minimise food waste (Wikström et al., 2014). Besides, packaging is being used as a marketing instrument (Silayoi, \& Speece, 2007), generating an expected value of almost one trillion dollars in 2020 globally (Qasim et al., 2020). The food and beverages industry has for decades accounted for the largest share of all the packaging produced, ranging from approximately $69 \%$ two decades ago (Pongrácz, 2007) to close to $85 \%$ nowadays (Qasim et al., 2020).

A rapidly growing component of the food industry is the food delivery and take-away sector (MarketWatch, 2020). This can partly be attributed to the development of online food ordering platforms (Hirschberg et al., 2016). In 2018, the global online food delivery and take-away market was estimated at approximately 54 billion USD (MarketWatch, 2020). This sector was expected to grow by $16.46 \%$ in the period 2019-2024 (MarketWatch, 2020), approximately 3.5\% per year (Hirschberg et al., 2016). Because of the current global pandemic crisis as a result of the COVID-19 virus, this sector is growing even more rapidly, as more restaurants started incorporating delivery and take-away of meals as part of their services. In the Netherlands for instance, FoodService Instituut Nederland (FSIN) reported that the annual revenue growth of the meal delivery by foodservice market was $37 \%$ in the period 2019-2020, instead of the expected $14 \%$ without the influence of the pandemic (Emerce, 2021). It is expected that the increase in this market sector will maintain also after the crisis.

Most packaging in the food industry and specifically in the food delivery and take-away sector is singleuse (UNEP, 2020). In the Netherlands alone, each year 876 million single-use meal containers are used in this sector (Recycling Netwerk Benelux, 2020a). There are significant environmental burdens associated with single-use meal containers, partly because of their low recyclability (Gallego-Schmid et al., 2019). This impact is two-fold: the depletion of the planet's natural resources (e.g. oil required for the production of plastics) and the pollution through waste generation (e.g. land/soil pollution by packaging ending up as litter in the environment because of irresponsible consumer behaviour) (Claudio, 2012; Gallego-Schmid et al., 2019; Pongrácz, 2007; Qasim et al., 2020).

Reusable food packings are being developed all over the world in order to address the environmental consequences of single-use packings (Sutton, 2020). Also within the food delivery and take-away sector, reusable meal containers are being developed and introduced. Recycling Netwerk Benelux is one of the organisations committed to phasing out single-use food packaging by supporting replacement with reusables (Recycling Netwerk Benelux, 2020b). One of the projects they are working on momentarily is focusing on switching from single-use to reusable meal containers in the food delivery and take-away sector in Belgium and the Netherlands. Restaurants in these two countries are considering this transition to reusables and several are currently already experimenting with it. This transition can be implemented in multiple ways with different environmental impacts. Reusable meal containers need to be recollected
and cleaned in order to be used again. Different options can be applied to these processes, which are referred to as system configurations in this research. The difference in environmental impacts creates a barrier for restaurant owners to decide what type of system is preferred. Part of the project is the development of an Excel tool, which actors within the food delivery and take-away sector in Belgium and the Netherlands can use to explore for different system configurations how the associated environmental impacts compare with each other.

Replacing single-use with reusable packaging is in line with the concept of the Circular Economy (CE) (Geissdoerfer et al., 2017). The CE differs from the linear economy because it focuses on reducing resource use through providing product services in a smarter way, reusing products, or recycling the materials after products or their parts cannot be (re)used anymore. Using fewer products and thereby less material results in fewer resources needed for producing new materials to be processed into new products, which simultaneously results in less waste generation. One of the main ideas is that using products smarter is more circular than reusing products and their parts, which is more circular than recycling (Potting et al., 2017). More circular means fewer resources and less environmental impact, which as a rule of thumb is true for the beforementioned hierarchy, although this still needs to be assessed for given circular initiatives.

Whether reusable packaging alternatives indeed perform better environmentally than single-use ones needs to be evaluated. Life Cycle Assessment (LCA) is a common way of assessing this for specific product systems by analysing all the impacts across their whole life cycle (ISO, 2006a; ISO, 2006b). The outcomes of the performed LCAs can thus indicate how different food delivery and take-away systems compare with each other and which configurations are environmentally preferred. LCA studies on reusable versus single-use packaging items have already been performed (Lewis et al., 2010; Raugei et al., 2009; Van der Harst \& Potting, 2014). However, reusable meal containers for food delivery and take-away systems are a relatively new concept. According to Gallego-Schmid et al. (2019), at the time their article got published, it was the very first LCA study on this specific topic, and the authors indicated that further research was required. Regarding the scientific relevance, this research focused on addressing this knowledge/literature gap and it was the first follow-up research on this topic to the author's knowledge.

The research was performed in collaboration with Recycling Netwerk Benelux. For the development of the Excel tool, a life cycle perspective was taken into account. In order to perform an LCA, but also to interpret the results properly, certain expertise is required (Thomas et al., 2020). Because of this, and the fact that the process is often expensive, there is a barrier for businesses to perform LCAs. Regarding the societal relevance, the input for the tool that was established as part of this research thus needed to be user-friendly. This entails that non-LCA experts need to be able to not only use the tool, but also interpret the results properly, in order to address the information/interpretation gap. The tool is not meant to replace full-blow (detailed) LCAs, but to provide actors with a good first indication of the environmental impacts and decrease the aforementioned barriers with that. The main aim of the research was to provide input for the tool, including an overview of the environmental impacts from reusable and single-use meal container systems with different configurations, and the most dominant life cycle stages contributing to these impacts.

The research question that was therefore established for this research was formulated as:
How do food delivery and take-away systems with reusable and single-use meal containers with different configurations compare with each other from an environmental life cycle perspective in Belgium and the Netherlands?

In order to answer this research question systematically, the following sub-questions were composed:

1. What are the different configurations food delivery and take-away systems can take in Belgium and the Netherlands?
2. How do the environmental impacts resulting from the different system configurations compare with each other?
3. What are the life cycle stages of food delivery and take-away systems that contribute most to the total impact?
4. How do the environmental impacts resulting from the complete life cycles of reusable meal container systems compare with those from single-use systems?

This research report continues with the Theoretical background chapter, in which the relevant background information for the research is described. This is followed by the Methodology chapter, which outlines the methodological approach followed in this research in order to answer the research question. Thereafter, the Results chapter provides an overview of the most important obtained results from the LCAs that were conducted. The results are then discussed in the Discussion chapter and the limitations encountered during the research are elaborated on. Finally, the conclusions are drawn based on the results, the research question is answered and recommendations for organisations in this industry sector and for further research on this topic are provided in the Conclusion and recommendations chapter.

## 2. Theoretical background

In this chapter, the theory deemed relevant as background information for conducting this research is described.

### 2.1 Circular Economy and 10 R strategies

The CE can be defined as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." (Geissdoerfer et al., 2017, p. 759). In order to address sustainable development, the CE concept recently started to be adopted by businesses (Urbinati et al., 2017) and on policymakers' agendas (Geissdoerfer et al., 2017). In essence, a CE can be achieved by transforming the dominant linear economy, which is based on a take, make, disposal model. This can be realised through focusing on reducing resource use and with that waste generation by minimising product use and keeping a product, and its parts and materials, in circulation for as long as possible with the highest possible value retention (Figure 1) (Geissdoerfer et al., 2017; Potting et al., 2018; Urbinati et al., 2017).


Figure 1: Overview of the Circular Economy concept (Potting et al., 2018).
It has to be noted that the CE discourse in Belgium and the Netherlands is ahead of those in most other countries. Many countries approach CE mainly as a waste management strategy as they are still in the stage of establishing a solid waste management system. Several Western European countries (among which Belgium and the Netherlands), however, have already established waste management systems. This typically resulted in high recycling rates and thus their focus is now on shifting from waste to resource management. Because of this, the current Belgian and Dutch economic systems can be expected
to be somewhere between a circular and a linear economy (Figure 2) (FPFSA, 2020; Potting et al., 2017). In this research, when referring to CE, the Belgian/Dutch CE discourse is taken as the reference point.


Figure 2: The transition from a linear towards a circular economy (Potting et al., 2017).
Often associated with the CE concept are the 10 R strategies (Figure 3) (Potting et al., 2017). These strategies relate to products and their functions and represent different kinds of strategies to minimise the required input for a product system, and thereby for an economy as a whole, or to ensure the output of one system becomes the input for another system in the most optimal manner (Kirchherr et al., 2017). The first three strategies focus on smarter product use and manufacture by delivering the same function with less product. The following five strategies focus on extending the lifespan of a product and its parts, thereby delivering the same function by using products longer. The final two strategies focus on the useful application of materials by recycling the materials in no longer usable products or their parts (Potting et al, 2017).


Figure 3: The 10 R strategies, hierarchically ordered in terms of circularity of a strategy (Potting et al., 2017).

There is a hierarchical order within these R strategies, meaning the higher the strategy is positioned, in principle, the less resource use and environmental impacts occur (i.e. the product becomes more circular). The higher strategies are thus preferred over the others (lower positioned) in relation to efficient resource use, environmental impacts and End-of-Life (EoL) disposal options. In this context, reusing (R3) goods is thus in general preferred over recycling (R8) because reusing often requires less energy and associated emissions than recycling goods (Ranta et al., 2018). However, the hierarchical order represents a rule of thumb and for specific cases it needs to be evaluated if the higher positioned strategies indeed perform better. This theory is relevant for the research because of the focus on reusable meal containers and single-use meal containers, which can be partly recycled at their EoL, and the comparison of how these product systems compare with each other.

In CE-based models, a resource remains within the system because it undergoes one or multiple of the 10 R strategies (Bag et al., 2020). The strategies can also be linked to the roles of different actors within a system from a life cycle perspective (Figure 4) (Potting et al., 2017). Certain actors, for instance restaurant owners and consumers, can play a role in realising the transition from one R strategy to another in specific life cycle stages, which is where LCA becomes relevant.


Figure 4: The roles of actors regarding the $R$ strategies within a system (Potting et al., 2017).

### 2.2 Life Cycle Assessment

LCA can be defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006a, p. 2). LCA was first introduced in the 1970s as merely an energy analysis, but the concept has developed rapidly since its introduction, especially from the 1990s onwards. The concept got extended from an energy analysis to a comprehensive environmental burden analysis (1970s), to complete Life Cycle Impact Assessment (LCIA) and Life Cycle Costing (LCC) models (1980s and 1990s), to Social-LCA (S-LCA) and

Consequential LCA (CLCA) (2000s) (Guinee et al., 2011). During the 1990s, when LCAs of similar products regularly produced conflicting results, there was a significant urge from businesses, science and society for the harmonisation and standardisation of the LCA framework, methodology and terminology (Van der Harst \& Potting, 2013).

Harmonisation and standardisation eventually resulted in the development of internationally accepted standards for the LCA procedures, namely ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b; Van der Harst \& Potting, 2013). ISO 14040 encompasses the principles and framework for LCA, including for instance how to define the goal and scope, how to compose and analyse the Life Cycle Inventory (LCI), and how to conduct the LCIA. Additionally, it provides descriptions of, among others, the relationships between the different phases of LCA and the main limitations of LCA (ISO, 2014a). The main limitations considered are incompleteness (in case of cut-offs/data gaps), inaccuracy (because of inadequate data quality in process analysis or input-output analysis as part of the inventory analysis) and irrelevance (because of inappropriate/unrepresentative impact categories) (Ekvall, 2002; ISO, 2014a). ISO 14044 encompasses the specific requirements for LCA and it also provides guidelines on the same elements as described above for ISO 14040 (ISO, 2014b). Both ISO 14040 and ISO 14044 were used during the research. In addition to ISO, other international guidelines have appeared in LCA, which entail more concrete methodologies for how to conduct LCA. For instance the ILCD Handbook, which provides guidance for addressing several choices that are not explicitly outlined in ISO (EC-JRC, 2010). Hence, the ILCD handbook was also consulted during the research.

According to ISO, LCA consists of four methodological phases (Figure 5) (ISO, 2006a; ISO, 2006b). This process is iterative, meaning that the results of phases are used in other phases, as indicated by the arrows. This implies that for instance certain components of the scope may require alteration as a result of the obtained data and information.


Figure 5: The four phases of Life Cycle Assessment (ISO, 2006a).

Phase 1 is the Goal and scope definition. The goal and scope of the study describe what the objective (goal) of the research is and what methodological approach (scope) will be used in order to achieve this goal. According to ISO 14040 (ISO, 2006a), there are four aspects of the goal definition that should be unambiguously stated (Table 1). Furthermore, several aspects need to be considered and described for the scope definition (Table 2). Especially the functional unit (FU) considered in the research and the description of the product systems are important aspects of the scope definition.

Table 1: The four aspects of goal definition (adapted from ISO, 2006a).

## Aspects of goal definition

1. The intended application of the research (what exactly is studied).
2. What the reasons are for conducting the research (why exactly this is studied).
3. What the intended audience of the research is (for who exactly this is studied).
4. An indication whether the comparative assertions will be disclosed to the public.

Table 2: The aspects of scope definition (adapted from ISO, 2006a).

| Aspects of scope definition |
| :--- |
| 1. The product systems that are to be studied. |
| 2. The functions of these product systems. |
| 3. The functional unit that will be used in the research. |
| 4. The system boundaries of the studied systems. |
| 5. The allocation procedures that will be applied. |
| 6. The selected impact categories and impact assessment methodology, and the |
| subsequent interpretation that will be used |
| 7. The data requirements. |
| 8. The assumptions that will be made. |
| 9. The limitations of the research. |
| 10. The quality requirements of the data. |
| 11. The type of critical review that will be applied. |
| 12. The type and format of the report that are required for the research. |

Phase 2 is the Inventory analysis. Inventory analysis quantifies the environmental inputs and outputs of the different processes making up a product system. The inventory analysis results in quantitative data tables with all elementary flows per FU. An elementary flow is defined as a "material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation" (ISO, 2006b, p. 3). In order to establish this, data have to be collected, both on the system inputs and outputs, for all different stages of the system.

Phase 3 is the Impact assessment. During the impact assessment, the data collected during the inventory analysis is converted into their environmental impacts in specific impact categories through classification and characterisation, and potentially normalisation and weighting. The shares of the contribution from life cycle stages to the total impact are often also indicated. The main goal of this phase is to evaluate and understand the extent and significance of the different impacts of the product system along the whole life cycle.

Phase 4 is the Interpretation. During the interpretation, the obtained results during phase(s) 2 and/or 3 are evaluated in relation to the defined goal and scope. This involves an evaluation of the robustness of the followed methodology and used data. Based on this, conclusions can be composed and recommendations can be provided. During this phase, the confidence and reliability of the LCA results are also examined through contribution and dominance analyses, and sensitivity and uncertainty analyses. Moreover, the limitations (e.g. inconsistencies/incompleteness) of the LCA must be described.

To summarise, LCA is nowadays a wellestablished method that can be used to analyse the different environmental impacts of each of the life cycle stages (Figure 6) of a product system (Baitz et al., 2013; Hoogmartens et al., 2014; Van der Harst \& Potting, 2013). According to Baitz et al. (2013), there are three basic criteria that LCA application in practice ought to accomplish (Table 3). It has to be noted however that there remains some room for a range of methodological choices, despite the standardisation of the LCA method by ISO (Van der Harst \& Potting, 2013). The theory on LCA was relevant for this research because LCAs were performed in order to assess and compare the impacts of reusable and single-use meal container product systems for food delivery and take-away, and the different configurations that are possible in those systems.


Figure 6: The life cycle stages of a product system.

Table 3: The three basic criteria that life cycle assessment application in practice must fulfil (adapted from Baitz et al., 2013).

## Basic criteria for life cycle assessment application in practice

1. To guarantee the credibility of information gathered and results generated, it needs to be reliable.
2. It needs to fit into existing information routines and practices in business to guarantee applicability.
3. In order to inform decision makers, it needs to provide quantitative and relevant information.

## 3. Methodology

In this chapter, the methodological choices that were taken in order to systematically answer the subquestions and with that the research question are outlined.

### 3.1 Research design

By following the research framework (Figure 7), the objectives of this research were established. Thorough literature review (Rowley \& Slack, 2004) and desk research (Juneja, 2020) provided the majority of the relevant theory and required data for this research. Consulting with multiple different types of organisations within this industry sector yielded additional required data and further insights into reusable meal container systems and the potential different configurations. The additional data and insights were provided through email contact and several expert meetings.

To analyse the obtained data, the software programmes SimaPro (PRé Sustainability, 2020b) and Microsoft Excel were used. The assessments provided the inventory and impact assessment results that were discussed and interpreted to answer the sub-questions and research question before drawing the conclusions. Finally, based on the conclusions, recommendations for actors within the food delivery and take-away sector in Belgium and the Netherlands, and for academics in regards to further required research on this topic, were composed.


Figure 7: Research Framework.
Initially, the comparative LCA started with two models composed of readily available data (section 3.2 provides more details on the LCA methodology). One of the initial models was representative for the
life cycle of a reusable meal container system and the other was representative for the life cycle of a single-use meal container system. The obtained data were assessed in SimaPro, and the resulting environmental impacts from the systems were exported to Excel. This export provided the basis of the input for developing the Excel tool. The development of the tool is not included in the Results chapter of this research, but it was composed in interaction with conducting the research. The two initial models were also analysed in Excel to check if the obtained results from the tool were equal to those from SimaPro. Thereafter, four additional models of systems from meal containers of different material types and models for the different configurations were composed in SimaPro. The obtained environmental impacts were again exported to Excel.

Additionally, resulting environmental impacts obtained from the assessments of individual datasets in SimaPro, that were not included in this research but were still relevant to include in the Excel tool (e.g. other material types that meal containers can potentially exist of) were also exported to Excel. After all required data for developing the tool were collected, the draft version of the tool was composed. This version, which already had to be close to the intended final version, was sent out to multiple different types of organisations working with reusable meal containers in order to receive feedback regarding the user-friendliness of the interface of the tool. In the meantime, additional data were collected to improve the SimaPro models where necessary. When a final check was performed to evaluate if all aspects of the life cycles of meal container systems had been correctly established and the obtained environmental impacts could thus be considered reliable, the research report was written. Lastly, the obtained feedback was processed and the final additions and improvements to the tool were established to obtain the version ready to be published. A Dutch version of the tool was also developed.

### 3.2 Life Cycle Assessment methodology

LCA consists of four phases. The scope definition usually outlines the approach for the whole LCA, however, the approaches for the LCI, the LCIA and the Interpretation were described under the eponymous sections for improved readability.

### 3.2.1 Phase 1: Goal and scope definition

The intended applications were the identification and comparative assertion of the environmental impacts resulting from food delivery and take-away system using reusable or single-use meal containers with different configurations in Belgium and the Netherlands. It remained unclear how the impacts resulting from those systems and the possible configurations compared with each other. Therefore, LCAs needed to be performed to determine whether reusable meal container systems can be considered environmentally preferred over single-use systems. The intended audience of the research is two-fold: actors in Belgium and the Netherlands that are interested in using the developed Excel tool to obtain a first indication of the environmental impacts and researchers interested in the results of the performed LCAs. The decision context can be classified as Situation C2 ('Accounting, excluding interactions with other systems') (EC-JRC, 2010) because allocation was used for addressing multifunctionality of the EoL stage and average data were taken for modelling background processes (Bjørn et al., 2018). The comparative assertions were not disclosed to the public.

There are two types of LCA, Attributional LCA (ALCA) and CLCA (Ekvall, 2020). The main difference between the two is illustrated in Figure 8. ALCA focuses on modelling a situation as it was, is, or will be, but without any changes to that system. CLCA focuses specifically on situational changes with the aim of indicating the impacts of the change to that system (which is compared with a certain baseline scenario). In accordance with the goal definition of this research, the modelling approach of the research was based on ALCA. However, CLCA was applied for some aspects (which is indicated in the report when it is the case).

Attributional LCA


What part of the global environmental burdens should be assigned to the product?

XX kg CO2-equ.
etc.

Consequential LCA


What is the impact of the product on the global environmental burdens?

ZZ kg CO2-equ.
etc.

Figure 8: Example of (the difference between) Attributional LCA and Consequential LCA (Ekvall, 2020).

## Function and functional unit

The function of the product systems is to provide food to customers in a desired and hygienic manner. Certain meals need to be at certain temperatures to live up to customer expectations or contain liquid components which the packaging should prevent from leaking. This function can be provided by different types of meal containers. Moreover, the function can differ per type of meal because these can differ significantly in regards to the required meal container characteristics. The research first identified the delivery and take-away meals that get ordered most in Belgium and the Netherlands in order to establish what types of meal containers are most commonly used. The FU considered in this research was: providing 43 meal delivery/take-away services with a 1.1 L volume meal container that can hygienically store food (containing liquid components). The amount of 43 services was included because the reusable meal container with the lowest technical lifetime of the three types considered in this research can be used 43 times on average. The volume of 1.1 L was included because it was expected that this would be suitable for the majority of meal types.

## Product system and system boundary

Providing food to customers in a desired and hygienic manner can be achieved in different ways, particularly with regards to reusable meal containers that need to be recollected and cleaned before they can be used again. There are thus different product system configurations possible. The flowcharts for the reusable and single-use meal container systems are indicated in Figure 9. The system boundaries were established according to a cradle-to-grave perspective following an ALCA approach. The life cycle stages Material production, Manufacturing and Distribution together form the cradle-to-restaurant component. This occurs before a restaurant can make use of a meal container for the services they provide, meaning these actors can often exert little influence on the processes that take place in this part of the life cycle (except for purchasing different types of meal containers). In this research, the Use stage of the life cycle consists of multiple processes, namely Meal preparation, Meal delivery/take-away, Customer cleaning, Retrieval and redistribution, and Professional cleaning. The latter three are only applicable to reusable meal container systems. The processes Meal preparation and Meal delivery/takeaway were not considered in this research, which is further explained in section 4.2. All Use stage processes were individually described and assessed in this research in order to provide a clear overview of what parts of the environmental impacts result from the different processes instead of the total impacts
resulting from the Use stage. Although the potential different system configurations for meal container systems considered in this research were identified in a later stage, these were already included in the flowchart to provide a complete overview. They are indicated in the processes Customer cleaning, Retrieval and Redistribution, and Professional cleaning of a reusable meal container system.


Figure 9: Flowcharts for a reusable and a single-use meal container system for food delivery and take-away.

## Limitations

Limitations that were encountered during performing the LCAs in this research were thoroughly documented and the most important ones are discussed in the Discussion chapter.

## Review and format

Regarding the critical review, this was performed during the whole LCA by the supervisors from Recycling Netwerk Benelux and by the supervisors and second reader from Utrecht University. The type and format of this research report are equal to those of a master's thesis. It therefore deviates partly from traditional LCA reporting.

### 3.2.2 Phase 2: Inventory analysis

During the inventory analysis, data were collected in order to compose the quantitative data tables for the different system configurations. There were two types of data required. First, (primary) data to describe and model foreground processes. These data and processes relate to product system characteristics such as meal container weights and lifetimes, transportation vehicles and distances, and
cleaning methods. These data were mainly obtained through analysing internal/unpublished documents from Recycling Netwerk Benelux and consulting with organisations working with reusable meal containers. Additional desk research was performed on websites of for instance retailers of dishwashers and retailers of electric delivery bicycles to complement these data. For several aspects, assumptions had to be made because specific data were either not available or could not be obtained due to confidentiality issues. Second, (secondary) data about background processes were required to assess the environmental impacts resulting from the different life cycle stages of meal container systems. These data were obtained by consulting the extensive LCI database ecoinvent 3.6 (Pré Sustainability, 2020a), which was included in the version of SimaPro used during this research.

To ensure the quality and reproducibility of the used inventory data and methods, all inventory data and methods used in this research were meticulously documented. An overview of all the ecoinvent datasets used for modelling in this research is provided in Appendix A. Where available, data as recent as possible and not older than five years, and representative for providing the function of the product systems in Belgium and the Netherlands were selected. The latter implies that data from the countries of origin for specific products/processes were used. Furthermore, average data for specific technologies were derived from the ecoinvent database, to ensure the representation of currently available technologies.

## Data tables

For the life cycle stages of meal container systems and for all possible configurations, an environmental data table was required. These tables were composed for each life cycle stage independently, to provide a clear overview of how the different meal container systems considered in this research compare with each other. The elementary flows per FU that were taken into account are the resources and energy that are required as input for a product system and the emissions and waste that result as the output of a product system. It was decided to compose the data tables in such a way that they indicate exactly how all process components were modelled, in order to ensure transparency and improve reproducibility. These tables therefore differ somewhat from commonly used inventory tables in LCA reporting. However, the emissions resulting from a product system can be derived from the results of the impact assessments presented in sections 4.2 and 4.5 .

## Allocation

Addressing multifunctionality is required for all multi-input or multi-output processes (Nicholson et al., 2009). In this case, allocation was required for the Material production and EoL stages. The Circular Footprint Formula (CFF) (Zampori \& Pant, 2019), suggested as an update to the European Commission's Product Environmental Footprint (PEF) method (EC-JRC, 2012) was applied. This method complies with ISO 14044:2006 and the ILCD handbook (Manfredi et al., 2015). The CFF takes into account burdens and credits between the life cycles of multiple product systems for the components material, energy and disposal, which are calculated by filling in all the required parameters (Equation 1). This equation therefore also takes into account the importance of allocation for the input into a product system, instead of only focusing on the output. Credits for the Material production stage were calculated and attributed when recycled content was used for the production of the meal containers. Credits for the EoL stage were calculated based on the avoided virgin material production in a subsequent product system as a result of recycling. Additionally, credits for the EoL stage were also calculated based on the avoided electricity and heat production (according to average Belgian and Dutch country grid mixes) as a result of incineration with energy recovery. The values for the parameters used in this research are documented in Appendix B. The correct credits were modelled manually in SimaPro because of the use of the ecoinvent system model Allocation, cut-off by classification.

Material

$$
\left(1-R_{1}\right) E_{V}+R_{1} \times\left(A E_{\text {recycled }}+(1-A) E_{V} \times \frac{Q_{\text {Sin }}}{Q_{p}}\right)+(1-A) R_{2} \times\left(E_{\text {recyclingEoL }}-E_{V}^{*} \times \frac{Q_{\text {Sout }}}{Q_{P}}\right)
$$

## Energy

$$
(1-B) R_{3} \times\left(E_{E R}-L H V \times X_{E R, \text { heat }} \times E_{S E, \text { heat }}-L H V \times X_{E R, \text { elec }} \times E_{S E, \text { elec }}\right)
$$

## Disposal

$$
\left(1-R_{2}-R_{3}\right) \times E_{D}
$$

### 3.2.3 Phase 3: Impact assessment

In order to express and analyse all inventory data per FU, the world's leading LCA-software SimaPro (v9.1) was used (PRé Sustainability, 2020b). Data obtained from SimaPro were exported to the software Microsoft Excel (v16) to compose the impact assessment graphs/tables and provide input for developing the Excel tool.

In order to conduct the impact assessment, a combination of the Cumulative Energy Demand (v1.11), CML-IA baseline (v3.06) and AWARE (v1.02) methods was applied (Boulay et al., 2018; Hischier et al., 2010). The CML-IA baseline method consists of 11 impact categories in total, to which all derived LCI results are attributed. The environmental impacts in this research are indicated as midpoint impact category results because midpoint characterisation results in lower modelling uncertainty than endpoint characterisation (Hauschild \& Huijbregts, 2015). Not all impact categories can be considered equally relevant for actors in the food delivery and take-away sector. Therefore, the impact categories that were selected from this method are Global warming, Ozone layer depletion, Photochemical oxidation, Acidification and Eutrophication. The impact categories Abiotic depletion, Abiotic depletion (fossil fuels), Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity and Terrestrial ecotoxicity were not included in this research. Because the environmental impacts associated with energy use and water use are also two important aspects of meal container systems to take into account during LCA, the impact categories Cumulative energy demand and Water use were also considered. For water use, the impact assessment method AWARE was applied because this is the recommended method by the European Commission Joint Research Centre (EC-JRC) (Boulay et al., 2018). Thus, the resulting environmental impacts for seven impact categories in total were assessed in this research (Table 4). The relevance of these impact categories was validated by the fact that these were used in a recently published LCA study on reusable and singleuse cups (Cottafava et al., 2021), of which the product systems are similar to those of reusable and single-use meal containers. After consulting with Recycling Netwerk Benelux, it was decided to only include the impact categories CED, GW and WU in the Excel tool. It was expected that the majority of the potential users would be familiar with these categories and the associated units in which the resulting environmental impacts are expressed.

Table 4:Overview of the seven environmental impact categories assessed in this research.

| Impact category | Abbreviation | Unit |
| :--- | :--- | :--- |
| Cumulative energy demand | CED | MJ |
| Global warming | GW | $\mathrm{kg} \mathrm{CO}_{2} \mathrm{eq}$ |
| Ozone layer depletion | OLD | $\mathrm{kg} \mathrm{CFC}^{2} 11 \mathrm{eq}$ |
| Photochemical oxidation | PO | $\mathrm{kg} \mathrm{C}_{2} \mathrm{H}_{4} \mathrm{eq}$ |
| Acidification (potential) | AP | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ |
| Eutrophication (potential) | EP | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ |
| Water use | WU | $\mathrm{m}^{3}$ |

### 3.2.4 Phase 4: Interpretation

The comparative LCA in this research went through several iterations. In the Results chapter, multiple LCAs were performed and therefore multiple types of results were obtained, which were already
interpreted during the process. The completeness and consistency of the obtained results were evaluated for each interpretation step.

In order to interpret the results, the significant issues based on the obtained results from phases 2 and 3 of the initial two models were identified first. These models were constructed in SimaPro using readily available data for each life cycle stage of meal container systems. This enabled the appliance of contribution and dominance analyses to determine the dominant life cycle stages (e.g. that contribute significantly to the total impact from the complete life cycles). A stage was considered dominant if it contributed for at least $10 \%$ (ISO, 2006b) of the total impact in at least four out of the seven impact categories. Additional data were collected for the dominant life cycle stages of reusable meal containers, namely Customer cleaning, Retrieval and redistribution, and Professional cleaning.

Thereafter, the models for the different system configurations were composed. The uncertainty analysis was performed by applying multiple data sources of alternative input data to the component included in an option that was expected to contribute most to the total impact of that system configuration. The uncertainty ranges were quantified accordingly and the average values were included in the modelling.

After the resulting environmental impacts from the complete life cycles of the three reusable and the three single-use meal container systems were assessed and compared, sensitivity analyses were performed to evaluate the robustness of the obtained results. When everything was checked and appeared correct, the main limitations encountered during performing the LCAs in this research were discussed in the Discussion chapter, which also entails the interpretation of the overall LCA process.

### 3.3 Environmental break-even points and return rates

After the resulting environmental impacts from the LCAs were obtained for all meal container systems, the values were used to calculate the environmental break-even points for each impact category. Breakeven point analysis can indicate when a certain product system is, in this case environmentally, preferred over another (Cottafava et al., 2021). In this research, it was used to determine after how many use cycles a certain reusable meal container system would be preferred if it would replace a certain singleuse meal container system, referred to as eBEP. There is a difference between the impacts per use cycle of reusable and single-use meal container systems. For reusable containers, there are associated impacts that result only once during the whole life cycle (from the Material production, Manufacturing, Distribution and EoL stages), referred to as Ro. Additionally, there are associated impacts that result from every use cycle because certain processes are required to be able to use the product again (from the Use stage, in this case the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages), referred to as Ru. For single-use containers, there are only associated impacts that result once during the whole life cycle because these are disposed of after each use cycle (from the Material production, Manufacturing, Distribution and EoL stages), referred to as So. Equation 2 was composed and used to calculate the environmental break-even points.

Equation 2: Overview of the equation used to calculate the environmental break-even points.

$$
\mathrm{eBEP}=\frac{\mathrm{Ro}}{(\mathrm{So}-\mathrm{Ru})}
$$

eBEP = Environmental Break-Even Point
Ro $=$ Impacts from the reusable life cycle that result only once
So = Impacts from the single-use life cycle (that result only once)
$\mathrm{Ru}=$ Impacts from the reusable life cycle that result from each use cycle
For instance, if $\mathrm{Ro}=10, \mathrm{So}=2$ and $\mathrm{Ru}=1.5$, the eBEP is: $10 /(2-1.5)=20$. It has to be noted that the break-even points will only be reached if the value of Ru is lower than the value of So (otherwise the
value of eBEP is negative). For every additional use cycle that the reusable is used after the break-even point, the additional environmental impacts that would otherwise result from using more single-use products are prevented. The eBEP values need to be rounded to above because it is not possible to undergo for instance 19.1 use cycles, and this value indicates that the break-even point is not yet reached after 19 use cycles. It is also possible that the eBEP value is higher than the technical lifetime of a reusable meal container. If this is the case, the break-even point will not be reached in practice, despite that the value of Ru is lower than the value of So.

An important aspect of product systems using reusable items considered in this research is the return rate. In this case, the return rate can be described as the share of reusable meal containers that in practice gets returned to the restaurant. In other words, the number of containers that are not recollected from the customers, or get lost somehow along the way, can be subtracted from the total number of containers to reach to return rate, which is often expressed in percentages. This return rate can limit the number of times a reusable meal container can be used in practice, even though the technical lifetime would allow the container to be used for more cycles. For instance, if 100 meal containers are distributed to customers, but only 95 (a return rate of $95 \%$ ) make it back to the restaurant, every time another 100 are distributed, five new containers are required. After 20 times of distributing 100 containers, in principle, the first 100 containers that were distributed are all replaced by new ones. Hence, with a return rate of $95 \%$, the average number of times a reusable container can be used in practice is 20 . The equation from Zampori \& Pant (2019) was used in this research to calculate the maximum number of average uses associated with certain return rates (Equation 3). The 'Number of reuse' and 'reuse rate' were referred to in this research as number of average uses and return rate respectively. The values for the number of average uses need to be rounded to below because it is not possible to use a container for instance 20.9 times.

Equation 3: Equation for calculating the number of average uses associated with a certain return rate (Zampori \& Pant, 2019).

$$
\text { Number of reuse }=\frac{1}{100 \%-\% \text { reuse rate }}
$$

### 3.4 Ethical data issues

Regarding ethical data issues, there was alignment with the internship organisation in respect to whether it was allowed to use the name Recycling Netwerk Benelux in this research. Documents that were handed in to the university were checked by Recycling Netwerk Benelux before. A standard internship contract (as supplied by Utrecht University) was signed by all parties (the internship organisation, the university and the student) in which a section regarding the Non-Disclosure Agreement is included. Because several organisations working with reusable meal containers that were consulted during this research indicated that there are confidentiality issues associated with a part of the provided data, these data are referred to as 'Confidential'.

## 4. Life cycle inventory and impact assessment results

### 4.1 Types of meals and associated types of meal containers

Identifying possible configurations of food delivery and take-away systems in Belgium and the Netherlands started by identifying the most commonly used types of meal containers in these countries. This was based on the most frequently ordered types of meals (Recycling Netwerk Benelux, 2021). It appeared that the most used types of meal containers can be divided into three main categories:

1. Boxes/Bowls
2. Pizza boxes
3. Fast-food packaging

Boxes/Bowls are suitable for containing the majority of meal types. They can be used for pasta dishes, salads, curries, even soups if they are leak-resistant, and any other type of ready-to-eat meals without a certain shape and/or size. After consulting with Recycling Netwerk Benelux, it was decided that these types of meal containers would be most suitable to include in this research.

Pizza boxes are a specific type of meal container, usually only suitable for pizzas. There are already several reusable pizza boxes being developed (and some already available on the market) (Michelangelo, 2021). Pizza boxes were not included in this research, however, since available alternatives are not applicable to the majority of meal types.

As opposed to pizza boxes, fast-food packings are applicable to multiple types of food. Nevertheless, these can still be considered a specific type of meal container because fast-food meals often exist of multiple components, packed separately. Fast-food packaging can therefore be better described as a collection of meal packings. Reusable options are already being developed for certain components of fast-food packaging (Goodwin, 2020), but there is not yet a good overall reusable alternative to pack a complete fast-food meal. Therefore, fast-food packaging was also not included in this research.

Three commonly used types of reusable boxes and three commonly used types of single-use boxes were considered in this research (Figure 10 and Figure 11).


Figure 10: Reusable polypropylene (PP) box on the left, reusable stainless steel (SS) box in the middle and reusable glass (GL) box on the right.


Figure 11: Single-use polypropylene ( $P P$ ) box on the left, single-use aluminium ( $A L$ ) box (with paper lid) in the middle and single-use paper $(P A)$ box on the right.

Table 5 provides an overview of the most important characteristics of these meal containers. The number of times the reusables can be used on average is without taking the actual return rates in practice into account. Later in this research, scenarios with different return rates were considered to provide a clear overview of how this influences the resulting environmental impacts. The author was in possession of the reusable PP box. A similar meal container was encountered in research by Gallego-Schmid et al. (2018). Because the weights were close to equal, it was decided that the weights reported in that research would be the most accurate and these were thus also included in this research. However, the dimensions might differ because these were not reported in that research. The weights of the single-use PA box are estimates because these had to be recalculated from the unit grams per square meter (gsm). The surfaces were calculated based on the dimensions that were available for a 1.1 L volume container (Kraft Packaging, 2019). An additional $10 \%$ of the weight was taken into account to account for the overlapping parts. The percentage of polyethylene coating was based on that for the paper lid of the single-use AL box (Gallego-Schmid et al., 2019).

Table 5: Overview of the most important characteristics of the meal containers considered in this research.

| Meal container | Material | Weight (g) | Lifetime (N) | Volume (L) | Source |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Reusable PP box | Polypropylene | 172 | 43 | 1.1 | Gallego-Schmid et al., 2018 |
|  | Silicone | 10 |  |  |  |
|  |  |  |  |  |  |
| Reusable SS box | Stainless steel | 381 | 200 | 1.1 | Except, 2019 |
|  |  |  |  |  |  |
| Reusable GL box | Glass | 575 | 50 | 1.1 | Gallego-Schmid et al., 2018 |
|  | Polypropylene | 87 |  |  |  |
|  | Silicone | 10 |  |  |  |
|  |  |  |  |  |  |
| Single-use PP box | Polypropylene | 31.5 | 1 | 0.67 | Gallego-Schmid et al., 2019 |
|  |  |  |  |  |  |
| Single-use AL box | Aluminium | 7.6 | 1 | 0.67 | Gallego-Schmid et al., 2019 |
|  | Paper | 6.6 |  |  |  |
|  | Polyethylene | 0.3 |  |  |  |
|  |  |  |  |  |  |
| Single-use PA box | Paper | 26.11 | 1 | 1.1 | Kraft Packging, 2019 |
|  | Polyethylene | 1.19 |  |  |  |

### 4.2 System configurations for the life cycle stages of meal containers

The different configurations for food delivery and take-way systems were identified for meals suitable to be packed in boxes/bowls. These were already included in the flowchart of a reusable meal container system (Figure 9). Each life cycle stage is described independently in this section in order to get a clear overview of what the potential configurations for a specific stage are. For the stages where different system configurations are possible, the resulting environmental impacts from the different options for a specific stage were already assessed and compared with each other. In this section, all values in the data tables were rounded to two numbers behind the decimal separator, except for values lower than 0.1, which were rounded to the first two non-zero numbers. All complete numbers were documented and can be provided by the author at request.

### 4.2.1 Material production

Boxes/Bowls can consist of different types of materials (Recycling Netwerk Benelux, 2019). Plastics (e.g. PP) are commonly used materials for single-use meal containers. Also often used are metals (e.g. AL) and paper (typically lined with a plastic coating to ensure that liquid components in a meal will not leak). For reusable meal containers, plastics are the most commonly used materials. Also often used are
rubbers (e.g. food-grade silicone), metals (e.g. SS) and glass (commonly white glass because this provides the possibility to see the food through the container).

The Material production stage was expected to be largely similar for all materials used in the different system configurations. The materials can either be produced from resources extracted from the planet or from recyclate (i.e. recycling of recovered materials from used products). In the case of plastic recyclate, according to EU law for food contact materials, there are limitations on the amount of recycled material that can be used in the production of food packaging (EFSA, 2012). That is, at least $95 \%$ of the recycled material must originate from previous food packaging (Fleurke et al., 2019). Whether produced from extracted resources or recyclate, in principle, both need to be gathered and transported to a manufacturing facility.

Table 6 provides an overview of the inventory data for the material production associated with the different types of meal containers considered in this research. The recycled contents were expected to be $0 \%$ for plastics, $75 \%$ for SS (Confidential), $40 \%$ for GL (FEVE, 2019), 32\% for AL (Gallego-Schmid et al., 2019) and $17 \%$ for PA (PPEC, 2011). The values for the recycled contents were calculated according to the CFF. Because there are no real different system configurations for the Material production stage, the resulting environmental impacts from this stage were not assessed and compared independently, but only included in the assessments of the complete life cycles.

Table 6: Inventory data used to model the material production associated with the different types of meal containers.

| System components | Quantity | Unit | Source | Comment |
| :--- | ---: | :--- | :--- | :--- |
| Reusable PP box |  |  |  |  |
| Polypropylene | 172.00 | g | Gallego-Schmid et al., 2018 |  |
| Silicone | 10.00 | g | Gallego-Schmid et al., 2018 | Silicone product selected as material |
|  |  |  |  | Values recalculated to 43 uses |
| Reusable SS box | 20.48 | g | Except, 2019 |  |
| Chromium steel | 49.15 | g | Confidential | Recycled content expected to be 75\% |
| Chromium steel recycled content | 12.29 | g |  | Sorting of steel based on iron scrap data |
| Sorting (for recycled content) | 12.29 | g |  | Recycling of steel based on iron scrap data |
| Recycling (for recycled content) |  |  |  | Values recalculated to 43 uses |
|  |  |  |  | Recycled content of flint glass is 40\% |
| Reusable GL box | 296.70 | g | Gallego-Schmid et al., 2018 |  |
| White glass | 158.24 | g | FEVE, 2019 | Sorting already included for glass recycling |
| White glass recycled content | 39.56 | g | ecoinvent, 2019 | Vale |
| Recycling (for recycled content) | 74.82 | g | Gallego-Schmid et al., 2018 |  |
| Polypropylene | 8.60 | g | Gallego-Schmid et al., 2018 | Silicone product selected as material |
| Silicone |  |  |  | Values recalculated to 1.1 L volume and 43 units |
|  |  |  |  | Values recalculated to 1.1 L volume and 43 units |
| Single-use PP box | $2,223.81$ | g | Gallego-Schmid et al., 2019* |  |
| Polypropylene |  |  |  | Recycled content of kraft paper is 17\% |
|  |  |  |  | Sorting already included for paper recycling |
| Single-use AL box | 364.85 | g | Gallego-Schmid et al., 2019* |  |
| Aluminium | 137.35 | g | Gallego-Schmid et al., 2019 | Recycled content of aluminium is 32\% |
| Aluminium (recycled content) | 34.34 | g | ecoinvent, 2019 | Sorting already included for aluminium recycling |
| Recycling aluminium (for recycled content) | 386.73 | g | Gallego-Schmid et al., 2019* |  |
| Paper | 53.86 | g | PPEC, 2011 | Recycled content of kraft paper is 17\% |
| Paper (recycled content) | 15.84 | g | ecoinvent, 2019 | Sorting already included for paper recycling |
| Recycling paper (for recycled content) | 21.18 | g | Gallego-Schmid et al., 2019* |  |
| Polyethylene |  |  |  |  |
|  | 931.78 | g | Kraft Packaging, 2019* | Values recalculated to 43 units |
| Single-use PA box | 129.78 | g | PPEC, 2011 |  |
| Paper | 38.17 | g | ecoinvent, 2019 |  |
| Paper (recycled content) | 51.03 | g | Gallego-Schmid et al., 2019* |  |
| Recycling paper (for recycled content) |  |  |  |  |
| Polyethylene | *Adjusted/Recalculated in order to be suitable for this specific research |  |  |  |
|  |  |  |  |  |

### 4.2.2 Manufacturing

The Manufacturing stage was also expected to be largely similar for all different system configurations. The manufacturing processes differ depending on the type of material used. For instance, shaping by injection moulding of plastics granulate is a manufacturing process often applied to meal containers made out of plastics (Shabra Plastics, 2013). Although there are these differences in this life cycle stage, in principle, a manufacturing process will always have to be applied to the material(s) in order to obtain a meal container with the correct shape and size.

Table 7 provides an overview of the inventory data for the manufacturing processes associated with the different types of meal containers considered in this research. Extrusion and thermoforming are applied to the material polypropylene in this specific case (Gallego-Schmid et al., 2018; Gallego-Schmid et al., 2019). It was assumed that sheet rolling and deep drawing are applied to the material steel. Melting and tempering are applied to the material glass (Gallego-Schmid et al., 2018). Sheet rolling and impact extrusion are applied to the material aluminium (Gallego-Schmid et al., 2019). The production of the paper lid was modelled based on the electricity and heat use required for this (Gallego-Schmid et al., 2019) because no suitable manufacturing process was encountered in SimaPro for this specifically. The manufacturing of the single-use PA box was modelled based on the electricity use required for manufacturing an ice cream cup of the same materials as indicated in research by Buccino et al. (2019). No suitable manufacturing process was encountered in SimaPro for this specifically and it was assumed that the properties of this box are equal to those of an ice cream cup in regards to for instance leakresistance. Also for the Manufacturing stage, the resulting environmental impacts were not assessed and compared independently, but only included in the assessments of the complete life cycles, because there are no real different system configurations for this stage.

Table 7: Inventory data used to model the manufacturing processes associated with the different types of meal containers.

| System components | Quantity | Unit | Source | Comment |
| :---: | :---: | :---: | :---: | :---: |
| Reusable PP box |  |  |  |  |
| Extrusion and thermoforming | 172.00 | g | Gallego-Schmid et al., 2018 | Silicone part already in product state |
| Reusable SS box |  |  |  | Values recalculated to 43 uses |
| Steel sheet rolling | 81.92 | g | Assumption | Manufacturing of steel assumed to be a combination of sheet rolling and deep drawing |
| Steel deep drawing | 81.92 | g | Assumption |  |
| Reusable GL box |  |  |  | Values recalculated to 43 uses |
| Glass melting (electricity) | 0.43 | MJ | Gallego-Schmid et al., 2018 | In MJ, because glass melting as a manufacturing process not included in SimaPro |
| Glass melting (heat) | 3.53 | MJ | Gallego-Schmid et al., 2018 |  |
| Glass tempering | 494.50 | g | Gallego-Schmid et al., 2018 |  |
| Extrusion and thermoforming | 74.82 | g | Gallego-Schmid et al., 2018 | For the polypropylene part |
| Single-use PP box |  |  |  | Values recalculated to 1.1 L volume and 43 units |
| Extrusion and thermoforming | 2,223.81 | g | Gallego-Schmid et al., 2019* |  |
| Single-use AL box |  |  |  | Values recalculated to 1.1 L volume and 43 units |
| Aluminium sheet rolling | 536.54 | g | Gallego-Schmid et al., 2019* |  |
| Aluminium impact extrusion | 536.54 | g | Gallego-Schmid et al., 2019* |  |
| Paper lid production (electricity) | 0.30 | MJ | Gallego-Schmid et al., 2019* | In $\mathrm{KJ} / \mathrm{MJ}$, because paper lid production as a manufacturing process not included in SimaPro |
| Paper lid production (heat) | 0.71 | KJ | Gallego-Schmid et al., 2019* |  |
|  |  |  |  |  |
| Single-use PA box |  |  |  | Values recalculated to 43 units |
| Paper box production (electricity) | 8.49 | MJ | Buccino et al., 2019* | Assumed to be equal to an ice cream cup |
| *Adjusted/Recalculated in order to be suitable for this specific research |  |  |  |  |

### 4.2.3 Distribution

The meal containers need to be distributed from the manufacturing facilities to the users. The type(s) of transportation mode used for this and the associated kilometres $(\mathrm{km})$ required to cover the distance(s) are largely dependent on the place of production of a meal container. The weight of a meal container is also of importance for the assessment of the impacts from this stage because the impacts from different freight transportation modes are based on the unit tonne-kilometre (tkm). All meal containers have to be stacked and packed (commonly in cardboard boxes) before they can be distributed, to avoid any damage to the products during the distribution. The Distribution stage is therefore largely similar for different types of meal containers.

Table 8 provides an overview of the inventory data for the distribution associated with the different types of meal containers considered in this research. The reusable PP and PA boxes considered in this research are produced in China (Gallego-Schmid et al., 2018). The reusable SS box is produced in South Korea (Greenweez, 2021). All the single-use boxes considered in this research are produced in China (Gallego-Schmid et al., 2019; Kraft Packaging, 2019). From China, the meal containers first have to be transported 150 km over road by using a lorry from the manufacturing facility to the port of Shanghai and then another $19,492.3 \mathrm{~km}$ over sea by using a container ship to the port of Rotterdam (GallegoSchmid et al., 2019). For the single-use PA box, equal distribution distances were assumed as for the other four boxes produced in China. From South Korea, it was expected that the meal containers also have to be transported 150 km over road by using a lorry from the manufacturing facility to the port of Inchon and then another $20,075.68 \mathrm{~km}$ (SEA-DISTANCES.ORG, 2021) over sea by using a container ship to the port of Rotterdam. It was assumed that all meal containers have to be transported another 150 km over road by using a lorry from the port of Rotterdam to the users, potentially via a distribution centre. The amounts of core board and polyethylene required for the packaging of the meal containers during the distribution were based on the values indicated in research by Gallego-Schmid et al. (2018; 2019). For the reusable SS box, the same amounts as for the reusable PP box were assumed. For the single-use PA box, the same amounts as for the single-use AL box were assumed. The manufacturing and EoL of the distribution packaging were not taken into account, because it was expected that the impacts resulting from this would be negligible in respect to the total impacts. Because the Distribution stage is largely similar for the different types of meal containers, the resulting environmental impacts from this stage were not assessed and compared independently, but only included in the assessments of the complete life cycles.

Table 8: Inventory data used to model the distribution associated with the different types of meal containers.


### 4.2.4 Meal preparation

No significant difference in environmental impacts was expected for this stage when a single-use meal container is replaced by a reusable one. This is because it was expected that the meal preparation process will be the same when the only difference is that, once the meal is finished, it has to be put into a reusable instead of a single-use meal container. The volume of the meal will also not be influenced by this. Therefore, this stage was not taken into account in the research.

### 4.2.5 Delivery/Take-away

For the Delivery/Take-away stage, there are multiple different system configurations. These are mainly based on the type of transportation vehicle used for the delivery/take-away process and the amount of km required for this. However, no significant difference in environmental impacts was expected for this stage when a single-use meal container is replaced by a reusable one. This is because the only difference would be the added weight of the meal container for the trip. It was not expected that switching to reusable meal containers would go accompanied with using different types of transportation vehicles. Generally, a reusable meal container of approximately the same size as a single-use container does weigh more. Nevertheless, the weight of the vehicle and the weight of the person performing the transportation
also have to be taken into account for the trip. It was expected that the relatively small part of added weight when a reusable meal container is transported instead of a single-use one is negligible in respect to the total weight. Therefore, this stage was also not taken into account in the research.

### 4.2.6 Customer cleaning

For the Customer cleaning stage, several different cleaning methods that can be applied were identified. Cleaning does not have to be applied to single-use meal containers, since these are disposed of after use. Most organisations working with reusable meal containers encourage the customers to either not clean it or only clean it shortly by rinsing with cold water. Dry wiping (with paper towels) is another option. However, this also depends on customer behaviour. It is therefore possible that the customer will thoroughly clean the meal container already after use anyway, even though this is not necessary, because they will also be professionally cleaned. It was expected that customers that will do this will either wash them by hand or wash them by using a dishwasher. Therefore, for the Customer cleaning stage, five different system configurations were taken into account in this research:

1. Handwashing
2. Dishwashing
3. Dry wiping (with paper towels)
4. Cold water rinsing
5. None

For handwashing, the data were obtained from research by Potting \& Van der Harst (2015) and complemented with data from research by Joseph et al. (2015) and data from research by Martin et al. (2018). It was expected that hot water and soap are required for handwashing a container, and that paper towels are used for drying it. It was assumed that two times the amounts required for washing one reusable cup are sufficient for washing one 1.1 L container. Thus, 2 L water, 0.44 MJ for heating the water (based on an $85 \%$ efficiency natural gas boiler), 2 g of soap and 4 paper towels are required (Potting \& Van der Harst, 2015). According to Joseph et al. (2015), a paper towel weighs 2 g . The treatment of wastewater required as a result of washing the container was added, of which the amount needs to be the same as the water input according to Martin et al. (2018).

For dishwashing, the data were obtained from research by Potting \& Van der Harst (2015) and complemented with data from research by Gallego-Schmid et al. (2018) and data from research by Martin et al. (2018). It was expected that a dishwasher uses 9.25 L water, 1 kWh electricity, 9.8 g soap and 1 g salt per wash (i.e. washing one load of dishes) (Potting \& Van der Harst, 2015). The load factor of a dishwasher (i.e. how many objects can fit into a dishwasher during one wash) for meal containers was expected to be 25 containers of 1.1 L volume (Gallego-Schmid et al., 2018). The treatment of wastewater required as a result of washing the container was also added (Martin et al., 2018). Furthermore, it was expected that the lifetime of an average dishwasher is 2,150 washing loads (Potting \& Van der Harst, 2015).

For dry wiping, it was expected that the same amount of paper towels is required as included in the handwashing option. Data for cold water rinsing were based on research by Binstock et al. (2013), who identified the rinsing of dishes specifically. It was assumed that 1.5 times the amount of water required for rinsing one dirty dinner plate is required for a 1.1 L volume meal container. Table 9 provides an overview of the collected inventory data for the five options. The values in the table are representative for 43 use cycles. The system component paper towels was modelled according to the CFF, an overview of this is provided in Appendix B. The impacts and credits from the EoL of paper towels were included in the options, to provide a clear overview of how the resulting environmental impacts from the customer cleaning options compare with each other. Wastewater treatment could not be modelled according to
the CFF, because there are no default values for the CFF parameters available for this. This is further discussed in the Discussion chapter.

Table 9: Inventory data used to model the different customer cleaning options, based on cleaning a 1.1 L volume meal container 43 times.

| System components | Quantity | Unit | Source | Comment |
| :--- | :---: | :--- | :--- | :--- | :--- |
| Option 1: Handwashing |  |  | Quantities from Potting \& Van der |  |
| Hater | 86 | L | Potting \& Van der Harst, 2015 | Harst, 2015 multiplied by 2 |

Because there are multiple system configurations possible for the Customer cleaning stage which can apply to all reusable meal container systems, the resulting environmental impacts from the options for this stage were already assessed and compared in this section.


Figure 12: Relative environmental impacts per impact category for four customer cleaning options.
Figure 12 illustrates of how the environmental impacts of the different customer cleaning options compare with each other. None customer cleaning was not included in this figure, because there are no environmental impacts associated with this. Handwashing results in the highest impacts in all seven impact categories. The impacts from cold water rinsing are by far the lowest for all impact categories. The findings thus indicate that, from these four options, cold water rinsing is the environmentally preferred option for the Customer cleaning stage and that handwashing is the worst option. The resulting impacts from handwashing are at least 9 times higher for all impact categories (ranging up to almost 43 times higher for CED) than those from cold water rinsing. If applying no customer cleaning after use is not an option, it would be best from an environmental perspective for organisations working with reusable meal containers to encourage the customers to apply cold water rinsing.

Table 10: Environmental impacts per impact category of four customer cleaning options. Absolute values per option are provided and the percentual contributions to those impacts of each component included in an option are also indicated.

| Impart category | CED | GW | OLD | PO | AP | EP | WU |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Unit | MJ | $\mathrm{kg} \mathrm{CO}_{2}$ eq | kg CFC-11 eq | $\mathrm{kg} \mathrm{C}_{2} \mathrm{H}_{4}$ eq | kg SO | eq | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-}$ |
| eq | $\mathrm{m}^{3}$ |  |  |  |  |  |  |
| Handwashing | $4.43 \mathrm{E}+01$ | $2.58 \mathrm{E}+00$ | $1.97 \mathrm{E}-07$ | $6.68 \mathrm{E}-04$ | $8.31 \mathrm{E}-03$ | $1.08 \mathrm{E}-02$ | $1.38 \mathrm{E}+00$ |
| Water (\%) | $1 \%$ | $1 \%$ | $2 \%$ | $1 \%$ | $2 \%$ | $1 \%$ | $128 \%$ |
| Soap (\%) | $11 \%$ | $18 \%$ | $13 \%$ | $36 \%$ | $17 \%$ | $64 \%$ | $56 \%$ |
| Paper towels (\%) | $38 \%$ | $28 \%$ | $25 \%$ | $36 \%$ | $61 \%$ | $22 \%$ | $31 \%$ |
| Energy (\%) | $49 \%$ | $51 \%$ | $59 \%$ | $24 \%$ | $16 \%$ | $2 \%$ | $1 \%$ |
| Wastewater (\%) | $1 \%$ | $2 \%$ | $2 \%$ | $2 \%$ | $4 \%$ | $11 \%$ | $-117 \%$ |
| Dishwashing | $1.98 \mathrm{E}+01$ | $8.65 \mathrm{E}-01$ | $9.27 \mathrm{E}-08$ | $2.41 \mathrm{E}-04$ | $4.62 \mathrm{E}-03$ | $4.43 \mathrm{E}-03$ | $3.70 \mathrm{E}-01$ |
| Water (\%) | $1 \%$ | $1 \%$ | $1 \%$ | $1 \%$ | $1 \%$ | $0 \%$ | $89 \%$ |
| Soap (\%) | $5 \%$ | $10 \%$ | $6 \%$ | $20 \%$ | $6 \%$ | $31 \%$ | $41 \%$ |
| Salt (\%) | $0 \%$ | $0 \%$ | $0 \%$ | $0 \%$ | $0 \%$ | $0 \%$ | $0 \%$ |
| Energy (\%) | $85 \%$ | $76 \%$ | $80 \%$ | $54 \%$ | $71 \%$ | $52 \%$ | $42 \%$ |
| Wastewater (\%) | $1 \%$ | $1 \%$ | $1 \%$ | $1 \%$ | $1 \%$ | $5 \%$ | $-80 \%$ |
| Dishwasher (\%) | $9 \%$ | $12 \%$ | $13 \%$ | $25 \%$ | $21 \%$ | $12 \%$ | $9 \%$ |
| Dry wiping | $1.66 \mathrm{E}+01$ | $7.34 \mathrm{E}-01$ | $4.84 \mathrm{E}-08$ | $2.41 \mathrm{E}-04$ | $5.07 \mathrm{E}-03$ | $2.37 \mathrm{E}-03$ | $4.25 \mathrm{E}-01$ |
| Paper towels (\%) | $100 \%$ | $100 \%$ | $100 \%$ | $100 \%$ | $100 \%$ | $100 \%$ | $100 \%$ |
| Cold water rinsing | $1.03 \mathrm{E}+00$ | $6.22 \mathrm{E}-02$ | $5.89 \mathrm{E}-09$ | $2.08 \mathrm{E}-05$ | $4.42 \mathrm{E}-04$ | $1.09 \mathrm{E}-03$ | $1.43 \mathrm{E}-01$ |
| Water (\%) | $52 \%$ | $41 \%$ | $46 \%$ | $40 \%$ | $29 \%$ | $7 \%$ | $1100 \%$ |
| Wastewater (\%) | $48 \%$ | $59 \%$ | $54 \%$ | $60 \%$ | $71 \%$ | $93 \%$ | $-1000 \%$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use
Absolute values of the resulting impacts for the four customer cleaning options are indicated in Table 10. The percentual contributions to those impacts of each component included in an option are also presented. The lower and upper boundary values of the uncertainty ranges for each option are indicated in Appendix C. Remarkably, the major contributing component to the impacts from handwashing for the majority of the impact categories is paper towels instead of energy. This aspect is further discussed in the Discussion chapter. The resulting impacts from the use of paper towels are relatively high. Because of this, dishwashing a meal container results in lower environmental impacts than dry wiping for the impact categories AP and WU.

### 4.2.7 Retrieval and redistribution

Many different system configurations are possible for the Retrieval and redistribution stage. After customers have finished their meal, they are left with an empty reusable meal container. These containers need to be retrieved from the customers and redistributed to the restaurants that will use them again. This starts with the different options for who is going to retrieve and redistribute the containers. This can be performed by the customer, deliverer, an intermediate, or a professional dishwashing organisation. The latter is only expected to be an option when the reusable meal containers are cleaned by a professional dishwashing facility and not by the restaurants themselves. There are organisations that offer retrieval and redistribution services, with professional cleaning in between (SwapBox, 2021).

Then there are also different options for how the retrieval and redistribution of the containers is arranged. Several examples are that a customer brings back the container after use to the restaurant, or the other way around, that the restaurant will pick up the container at the customers' address after use. This can
be done the same day the meal containers are being used or at a later stage. For instance, the next time that a meal gets delivered to a certain address, the container from the previous delivery can be retrieved at the same time. It depends on a restaurants' preferences regarding how quickly a meal container is retrieved after use whether it would be necessary to make use of for instance a retrieval round at the end of the day. It is best in respect to the hygiene and durability of the meal container when it is retrieved and cleaned within the first 24 hours after use (YOYO.BoostReuse, 2020). If it is not necessary to retrieve and clean the meal containers quickly after use, organisations are trying to make this process as convenient as possible for customers. Several options are by creating drop-off points that are close to the customers' home or working with at-home exchanges or pick-ups (Recycling Netwerk Benelux, 2019).

Finally, there are different options in respect to what type(s) of transportation vehicle will be used to retrieve and redistribute the meal containers, and the associated amount of km required for this. It is expected that this will largely correspond with the type(s) of transportation vehicle already used by the restaurants and the amount of km required on average to deliver meals. The most commonly used types of transportation vehicle for delivering meals in Belgium and the Netherlands are (electric) bicycles, (electric) scooters and (electric) cars (Cashdesk, 2018). However, it can be expected that a van will be used when making use of drop-off points because this type of vehicle can carry more containers at once.

This research included the assessment of the environmental impacts deriving from different retrieval and redistribution scenarios. To the author's knowledge, this aspect has not been researched before. The identified scenarios are illustrated in Figure 13.


Figure 13: Overview of the different scenarios for the Retrieval and redistribution stage (adjusted from Recycling Netwerk Benelux, 2019).

Unfortunately, hardly any data were available for this life cycle stage. Consulting with different types of organisations within this industry sector led to promising insights into these systems, providing the basis for the assumptions for the different scenarios. However, specific data for the different characteristics (e.g. the transportation vehicles used, amount of km travelled and the amount of containers recollected at once) of these scenarios could not be obtained. Organisations indicated that they either did not have this data available (because the pilot trials are still in an early stage or because they do not track their containers) or that they could not provide this due to confidentiality issues. Nevertheless, a table containing the data used to model different scenarios was composed, based on
expert judgement assumptions (Table 11). Also in this table, the values are representative for 43 use cycles.

Table 11: Inventory data used to model the different retrieval and redistribution scenarios, based on recollecting 43 meal containers.

| System components | Quantity | Unit | Source | Comment |
| :---: | :---: | :---: | :---: | :---: |
| Scenario 1a: Retrieval round electric bicycle |  |  |  |  |
| Electric bicycle* | 21.50 | pkm | Assumption | Average of 0.50 km per container assumed |
|  |  |  |  |  |
| Scenario 1b: Retrieval round scooter |  |  |  |  |
| Scooter* | 21.50 | pkm | Assumption | Average of 0.50 km per container assumed |
|  |  |  |  |  |
| Scenario 2a: Drop-off point van (100 containers) |  |  |  |  |
| Van* | 3.44 | km | Assumption | Van collects 100 containers at once and thus an average of 0.080 km per container assumed |
|  |  |  |  |  |
| Scenario 2b: Drop-off point van (200 containers) |  |  |  |  |
| Van* | 1.72 | km | Assumption | Van collects 200 containers at once and thus an average of 0.040 km per container assumed |
|  |  |  |  |  |
| Scenario 2c: Drop-off point electric bicycle (42 containers) |  |  |  |  |
| Electric bicycle* | 8.19 | pkm | Assumption | Electric bicycle can carry 42 containers at once and thus an average of 0.19 km per container assumed |
|  |  |  |  |  |
| Scenario 3: At-home/At-restaurant exchanges |  |  |  |  |
| (No components) |  |  | Assumption | No additional traveling distances assumed |
| *Uncertainty ranges taken into account |  |  |  |  |

For the retrieval round, it was assumed that this will be performed by an electric bicycle (scenario 1a). Additionally, it was assumed that on average 0.5 km will have to be travelled to collect a container (one km per address and two containers per address). Because it is not certain that an electric bicycle will be used for this, the same retrieval round performed by a scooter was also assessed (scenario 1b).

Different data were obtained for the average range in which restaurants deliver, namely 3.5 km (Deliveroo Belgium, personal communication, May 25, 2021) and 5-10 km (Ebike Nederland, 2019). For the drop-off point, it was assumed that this is located on average 4 km away from a restaurant. Thus, 8 km will have to be travelled in total from a restaurant to the drop-off point and back. In scenarios 2 a and 2 b , it was assumed that a van collects the containers once there are 100 and 200 respectively at a drop-off point. It is also possible that other transportation modes will be used for collecting the containers from a drop-off point. Therefore, in scenario 2c, it was assumed that an electric bicycle is used for this. The average amount of containers an electric bicycle can collect from a drop-off point is 42. This value was based on the dimensions of the reusable PP box ( $181 \times 128 \times 88 \mathrm{~mm}$ ) (Lock\&Lock, 2021) and the reusable SS box ( $180 \times 180 \times 50 \mathrm{~mm}$ ) (Tiffin, 2020), and those of an average delivery box ( $550 \times 410 \times 420 \mathrm{~mm}$ ) that can be installed on an electric bicycle (Engels Logistics, 2020). The average was based on the fact that 36 reusable PP boxes or 48 reusable SS boxes can fit into a delivery box.

For the at-home/at-restaurant exchanges, it was expected that no additional transport is required for this and thus no resulting environmental impacts are associated with this. The containers can be collected the next time a meal is being delivered to a certain address or they can be brought back the next time the customer comes to the restaurant for take-away.

Because there are multiple system configurations possible for the Retrieval and redistribution stage which can apply to all reusable meal container systems, the resulting environmental impacts from the scenarios for this stage were already assessed and compared in this section.


Figure 14: Relative environmental impacts per impact category of the five retrieval and redistribution scenarios assessed in this research.

The relative environmental impacts per impact category of the different retrieval and redistribution scenarios that were assessed are presented in Figure 14. The associated absolute values are indicated in Table 12. The lower and upper boundary values of the uncertainty ranges for each option are indicated in Appendix C. Scenario 1b, making use of a retrieval round by a scooter, results in the highest impacts in six out of the seven impact categories. This scenario is thus the least environmentally preferred. Especially for the impact category PO, the resulting impacts from this scenario are significantly higher than those from all other scenarios (at least 31 times higher). This can mainly be attributed to the formation of Secondary Organic Aerosols (SOA) that takes place during the incomplete fuel combustion of two-stroke scooters (Platt et al., 2014). Gasoline contains aromatic Volatile Organic Compounds (VOC), of which through photochemical oxidation SOA is produced. Benzene and Toluene are two of these VOCs, which are damaging to human health (Mögel et al., 2011), that contribute for a large part to the total resulting impact for this impact category. Additionally, carbon monoxide and sulfur dioxide also contribute for a large part. Only for the impact category WU, scenario 1a, making use of a retrieval round by an electric bicycle, results in a higher impact than scenario 1 b . It findings indicate that scenario 2 c , making use of a drop-off point from which the containers are collected by an electric bicycle, is the environmentally preferred option. This scenario results in the lowest impact for each of the seven impact categories.

Table 12: Absolute values of the resulting environmental impacts per impact category from each of the retrieval and redistribution scenarios.

| Impact category | CED | GW | OLD | PO | $\mathbf{A P}$ | $\mathbf{E P}$ | WU |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Unit | MJ | $\mathrm{kg} \mathrm{CO}_{2}$ eq | $\mathrm{kg} \mathrm{CFC}-11 \mathrm{eq}$ | $\mathrm{kg} \mathrm{C}_{2} \mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}^{3}$ | $\mathrm{~m}^{3}$ |
| Scenario 1a | $7.33 \mathrm{E}+00$ | $4.52 \mathrm{E}-01$ | $3.25 \mathrm{E}-08$ | $1.96 \mathrm{E}-04$ | $3.86 \mathrm{E}-03$ | $1.66 \mathrm{E}-03$ | $1.29 \mathrm{E}-01$ |
| Scenario 1b | $2.86 \mathrm{E}+01$ | $2.02 \mathrm{E}+00$ | $2.76 \mathrm{E}-07$ | $7.22 \mathrm{E}-03$ | $6.74 \mathrm{E}-03$ | $1.72 \mathrm{E}-03$ | $1.27 \mathrm{E}-01$ |
| Scenario 2a | $2.04 \mathrm{E}+01$ | $1.30 \mathrm{E}+00$ | $2.02 \mathrm{E}-07$ | $2.33 \mathrm{E}-04$ | $5.22 \mathrm{E}-03$ | $1.55 \mathrm{E}-03$ | $1.24 \mathrm{E}-01$ |
| Scenario 2b | $1.02 \mathrm{E}+01$ | $6.49 \mathrm{E}-01$ | $1.01 \mathrm{E}-07$ | $1.17 \mathrm{E}-04$ | $2.61 \mathrm{E}-03$ | $7.75 \mathrm{E}-04$ | $6.22 \mathrm{E}-02$ |
| Scenario 2c | $2.79 \mathrm{E}+00$ | $1.72 \mathrm{E}-01$ | $1.24 \mathrm{E}-08$ | $7.47 \mathrm{E}-05$ | $1.47 \mathrm{E}-03$ | $6.34 \mathrm{E}-04$ | $4.93 \mathrm{E}-02$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use

### 4.2.8 Professional cleaning

The Professional cleaning stage is an essential stage for reusable meal container systems to work in practice because they need to be professionally cleaned after use before they can be used again, to ensure food hygiene and safety. There are many different types of professional dishwashers that restaurants can make use of for cleaning their meal containers (Styles et al., 2013). However, these are relatively expensive and it can thus be expected that for instance smaller restaurants do not have a professional dishwasher, but instead have a conventional dishwasher (which most people have at home). Besides cleaning the meal containers professionally themselves, restaurants also have the possibility to outsource this stage (SwapBox, 2021). There are professional dishwashing organisations that have a dishwashing facility where products can be professionally cleaned, often on a much larger scale than what would take place in a single restaurant.

In order to be able to assess all different system configurations within the available timeframe of this research, a selection of three different options, representative for the majority of different types of professional dishwashing, was made:

1. Conventional dishwashing
2. Door/Hood-type dishwashing (referred to as professional dishwashing)
3. Conveyer-type dishwashing (referred to as industrial dishwashing)

For the professional cleaning options, the environmental impacts resulting from the dishwashers themselves were not taken into account. The reason for this is that professional and industrial dishwashers are not included in the ecoinvent database and thus the associated impacts could not be modelled accurately. In order to provide a clear overview of how the resulting impacts from the professional dishwashing options compare with each other, it was decided to exclude the system component dishwasher also for the conventional dishwashing option. The other data for this option are equal to those included in the Customer cleaning stage. Data for professional and industrial dishwashing were obtained from KIDV (2020) and complemented with wastewater treatment based on research by Martin et al. (2018). It was expected that a professional dishwasher uses 0.43 L water, 1.38 g detergent ( NaOH solution) and 0.074 MJ electricity per 1.0 L volume object cleaned. For an equally sized object, it was expected that an industrial dishwasher uses 0.27 L water, 2.08 g detergent ( NaOH solution) and 0.029 MJ electricity. The data were recalculated to be representative for a 1.1 L volume container. It is important to note that electricity use of medium voltage was included for industrial dishwashing because it was expected that this is part of the production industry (Pintusava, 2019). Table 13 provides an overview of the collected inventory data for the three options. The values in the table are representative for 43 use cycles.

Table 13: Inventory data used to model the different professional cleaning options, based on cleaning a 1.1 L volume meal container 43 times.

| System components | Quantity | Unit | Source | Comment |
| :---: | :---: | :---: | :---: | :---: |
| Option 1: Conventional dishwashing |  |  |  | Same as for customer dishwashing, except dishwasher excluded |
| Water | 15.91 | L | Potting \& Van der Harst, 2015 |  |
| Electricity | $5.57 \pm 0.62$ | MJ | Bosch, 2020; Potting \& Van der Harst, 2015 | Uncertainty range based on 0.80 and 1.00 kWh per dishwasher load |
| Soap | 16.86 | g | Potting \& Van der Harst, 2015 |  |
| Salt | 1.72 | g | Potting \& Van der Harst, 2015 |  |
| Wastewater treatment | 15.91 | L | Martin et al., 2018 |  |
|  |  |  |  |  |
| Option 2: Professional dishwashing |  |  |  |  |
| Water | 20.41 | L | KIDV, 2020 | Uncertainty range based on differences in volumes (load factor) |
| Electricity | $3.50 \pm 1.26$ | MJ | Carbotech, 2014; Harnoto, 2013; KIDV, 2020 |  |
| Detergent ( NaOH ) | 65.22 | g | KIDV, 2020 | Sodium hydroxide in 50\% solution state |
| Wastewater treatment | 20.41 | L | Martin et al., 2018 |  |
|  |  |  |  |  |
| Option 3: Industrial dishwashing |  |  |  |  |
| Water | 12.93 | L | KIDV, 2020 | Uncertainty range based on differences in volumes (load factor) |
| Electricity | $1.37 \pm 0.14$ | MJ | Carbotech, 2014; KIDV, 2020 |  |
| Detergent ( NaOH ) | 98.23 | g | KIDV, 2020 | Sodium hydroxide in 50\% solution state |
| Wastewater treatment | 12.93 | L | Martin et al., 2018 |  |

Because there are also multiple system configurations possible for the Professional cleaning stage which can apply to all reusable meal container systems, the resulting environmental impacts from the options for this stage were already assessed and compared in this section.


Figure 15: Relative environmental impacts per impact category for each of the professional cleaning options.
Figure 15 illustrates how the environmental impacts of the different professional cleaning options compare with each other. It can be observed that conventional dishwashing results in the highest impacts in six out of the seven impact categories. This is thus the least environmentally preferred option.

Interestingly, both professional and industrial dishwashing result in higher impacts than conventional dishwashing for the impact category OLD. This can mainly be attributed to the use of the NaOH solution as the detergent. The NaOH solution contains higher amounts of ChloroFluoroCarbons (CFC), which are used in cleaning products because of their effectiveness in degreasing dishes (Kim et al., 2016), than soap. For the other six impact categories, industrial dishwashing results in the lowest impacts. The findings thus indicate that this is the environmentally preferred option for the Professional cleaning stage. However, it has to be taken into account that this option might require additional transportation if a restaurant outsources the process. The impacts of this option are then expected to be higher. This was not assessed in this research, because previous research by Cottafava et al. (2021) indicated that the impacts resulting from industrial dishwashing are still dominated by the electricity use if the additional transport to a dishwashing facility required is relatively small ( 20 km ). Even with distances up to 50 km , this option was still environmentally preferred over the other cleaning options. It was expected in this research that transport to industrial dishwashing facilities in Belgium and the Netherlands would not exceed this distance.

Table 14: Environmental impacts per impact category of the professional cleaning options. Absolute values per option are provided and the percentual contributions to those impacts of each component included in an option are also indicated.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | $\mathrm{kg} \mathrm{CO}_{2}$ eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}{ }_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Conventional dishwashing | $1.81 \mathrm{E}+01$ | $7.61 \mathrm{E}-01$ | 8.02E-08 | $1.81 \mathrm{E}-04$ | 3.64E-03 | $3.88 \mathrm{E}-03$ | $3.37 \mathrm{E}-01$ |
| Water (\%) | 1\% | 1\% | 1\% | 1\% | 1\% | 0\% | 97\% |
| Soap (\%) | 5\% | 12\% | 6\% | 26\% | 8\% | 35\% | 45\% |
| Salt (\%) | 0\% | 0\% | 0\% | 0\% | 0\% | 0\% | 0\% |
| Energy (\%) | 94\% | 87\% | 92\% | 72\% | 90\% | 59\% | 46\% |
| Wastewater (\%) | 1\% | 1\% | 1\% | 1\% | 2\% | 6\% | -88\% |
| Professional dishwashing | $1.22 \mathrm{E}+01$ | 5.15E-01 | 1.01E-07 | $1.04 \mathrm{E}-04$ | 2.58E-03 | 1.91E-03 | $2.21 \mathrm{E}-01$ |
| Water (\%) | 1\% | 1\% | 1\% | 2\% | 1\% | 1\% | 190\% |
| Detergent (\%) | 10\% | 16\% | 52\% | 16\% | 16\% | 9\% | 39\% |
| Energy (\%) | 87\% | 80\% | 46\% | 79\% | 79\% | 76\% | 44\% |
| Wastewater (\%) | 1\% | 2\% | 1\% | 3\% | 3\% | 14\% | -172\% |
| Industrial dishwashing | $6.15 \mathrm{E}+00$ | 2.98E-01 | 9.82E-08 | 5.83E-05 | $1.45 \mathrm{E}-03$ | 9.96E-04 | 1.90E-01 |
| Water (\%) | 1\% | 1\% | 0\% | 2\% | 1\% | 1\% | 141\% |
| Detergent (\%) | 32\% | 43\% | 81\% | 44\% | 44\% | 27\% | 69\% |
| Energy (\%) | 65\% | 53\% | 18\% | 50\% | 51\% | 54\% | 19\% |
| Wastewater (\%) | 1\% | 2\% | 1\% | 4\% | 4\% | 18\% | -128\% |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use

Table 14 contains absolute values of the environmental impacts of the professional cleaning options. Again, the percentual contributions to those impacts of each component included in an option are also presented. The lower and upper boundary values of the uncertainty ranges for each option are indicated in Appendix C. From the table, it can be observed that the energy use contributes most to the impacts for the majority of the impact categories for all options. Nevertheless, the impacts resulting from the use of soap/detergent ( NaOH solution) are also significant for the majority of the impact categories, which especially becomes visible from the percentual contributions to the resulting impacts from industrial dishwashing.

The percentual contributions to the impact category WU illustrate something remarkable. Although it might be expected that the water used for dishwashing would be the highest contributing process to this
impact category, this cannot easily be concluded. When taking into account that the negative impacts for this category from wastewater treatment are solely the result of the water input, it can be argued that soap/detergent and energy use contribute more to this impact category. This is because during for instance the production of soap/detergent and energy, a certain amount of water is required which can be considered lost in the process.

### 4.2.9 End-of-Life

The EoL stage is the final stage of the life cycle of a meal container. Even reusable containers reach their EoL stage after a certain time. Multiple disposal options can be applied, such as recycling, incinerating (with energy recovery) and landfilling. Which type of disposal can be applied to specific meal containers depends largely on the materials they consist of. In order to be able to assess this stage properly in this research, average waste disposal scenarios in Belgium and the Netherlands for different types of materials were identified.

In Belgium and the Netherlands, the percentage of a material that is recycled depends on the specific type of material (Belgische Federale Overheidsdiensten, 2020; Van Velzen et al., 2019). Table 15 provides an overview of the recycling percentages that were considered in this research. For Belgium, the percentages for plastic and glass recycling were corrected from $44.5 \%$ to $29 \%$ and from $100 \%$ to $90.15 \%$ respectively. This is because these percentages for these two material types are more realistic since the percentages reported are overrated according to Recycling Netwerk Benelux (Buurman, 2019; Recycling Netwerk Benelux, 2018). For the Netherlands, the percentages according to the new measurement method were included in this research because these provide a more realistic indication of how much of the materials are recycled. This is because the percentages calculated according to the old method also have to be adjusted for losses that occur at the recyclers in the preparation of the recycling processes (Brouwer et al.,

Table 15: Overview of the recycling percentages from 2017 for Belgium and the Netherlands that were considered in this research.

| Material | Recycling percentages BE | Recycling percentages NL |
| :--- | ---: | ---: |
| Glass | $90.15 \%$ | $71 \%$ |
| Paper | $92.9 \%$ | $87 \%$ |
| Plastics | $29 \%$ | $35 \%$ |
| Metals | $98.5 \%$ | $95 \%$ |
| Wood | $83.7 \%$ | $73 \%$ | 2019). The lower boundary values for glass and plastics were included.

The percentage of materials that cannot be recycled will be disposed of by other means. These data were based on the percentages for average municipal solid waste treatment in Belgium and the Netherlands, meaning $98 \%$ and $97 \%$ respectively were expected to be incinerated in facilities that recover electricity and heat during this process (Zampori \& Pant, 2019). The amounts of electricity and heat that are recovered during the incineration process are $20 \%$ and $23 \%$ respectively of the energy content of the waste in the Netherlands (RVO, 2020). Because of a lack of encountered accurate data for this in Belgium, the same percentages as in the Netherlands were assumed. How much energy can be recovered depends on the calorific values (i.e. how much energy a material contains per kilogram) of each material specifically (Fruergaard et al., 2010). It has to be noted that not all material types are suitable for incineration with energy recovery. Only materials containing organic matter are suitable for this (Patil et al., 2014). Thus, the waste treatment of waste that is not recycled and from which energy cannot be recovered during incineration was referred to as disposal.

Table 16 and Table 17 provide an overview of the inventory data for the EoL stage associated with the different types of meal containers considered in this research. All values included were calculated according to the CFF. Because for the Netherlands the most accurate and complete data were encountered during this research, the modelling was based on average Dutch waste scenarios for the
different materials. Material leakage (i.e. materials that are not properly disposed of) of $2.5 \%$, which is common for plastics (Laurin, 2018), was included in the calculations for all material types. Because of the use of average waste scenarios, there are no real different system configurations for the EoL stage and thus the resulting environmental impacts from this stage were not assessed and compared independently, but only included in the assessments of the complete life cycles.

Table 16: Inventory data used to model the End-of-Life stage associated with the different types of reusable meal containers.

| System components | Quantity | Unit | Source | Comment |
| :---: | :---: | :---: | :---: | :---: |
| Reusable PP box |  |  |  |  |
| Sorting | 29.35 | g |  | Sorting based on polyethylene data |
| Recycling | 29.35 | g |  | Recycling based on polyethylene data |
| Polypropylene (retrieved from recycling) | -26.41 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Incinerating | 57.60 | g | Zampori \& Pant, 2019 | Polypropylene data also assumed for silicone |
| Electricity (retrieved from polypropylene) | -0.43 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of polypropylene is $40.34 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from polypropylene) | -0.49 | MJ | RVO, 2020; TNO, 2021 |  |
| Electricity (retrieved from silicone) | -0.0095 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of silcone is $10.00 \mathrm{MJ} / \mathrm{kg}$ (equals rubber assumed) |
| Heat (retrieved from silicone) | -0.011 | MJ | RVO, 2020; TNO, 2021 |  |
| Disposal | 3.56 | g | Zampori \& Pant, 2019 | Polypropylene data also assumed for silicone |
|  |  |  |  |  |
| Reusable SS box |  |  |  | Values recalculated to $\mathbf{4 3}$ uses |
| Sorting | 60.70 | g |  | Sorting based on iron scrap data |
| Recycling | 60.70 | g |  | Recycling based on iron scrap data |
| Chromium steel (retrieved from recycling) | -60.70 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Disposal | 3.99 | g | Zampori \& Pant, 2019 |  |
|  |  |  |  |  |
| Reusable GL box |  |  |  | Values recalculated to $\mathbf{4 3}$ uses |
| Recycling glass | 273.85 | g | ecoinvent, 2019 | Sorting already included for glass recycling |
| White glass (retrieved from recycling) | -273.85 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Sorting polypropylene | 12.77 | g |  | Sorting based on polyethylene data |
| Recycling polypropylene | 12.77 | g |  | Recycling based on polyethylene data |
| Polypropylene (retrieved from recycling) | -11.49 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Incinerating polypropylene and silicone | 27.06 | g | Zampori \& Pant, 2019 | Polypropylene data also assumed for silicone |
| Electricity (retrieved from polypropylene) | -0.19 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of polypropylene is $40.34 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from polypropylene) | -0.21 | MJ | RVO, 2020; TNO, 2021 |  |
| Electricity (retrieved from silicone) | -0.0081 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of silcone is $10.00 \mathrm{MJ} / \mathrm{kg}$ (equals rubber assumed) |
| Heat (retrieved from silicone) | -0.0094 | MJ | RVO, 2020; TNO, 2021 |  |
| Disposal glass | 139.82 | g | Zampori \& Pant, 2019 |  |
| Disposal polypropylene and silicone | 1.67 | g | Zampori \& Pant, 2019 | Polypropylene data also assumed for silicone |

Table 17: Inventory data used to model the End-of-Life stage associated with the different types of single-use meal containers.

| System components | Quantity | Unit | Source | Comment |
| :---: | :---: | :---: | :---: | :---: |
| Single-use PP box |  |  |  | Values recalculated to 1.1 L volume and 43 units |
| Sorting | 379.44 | g |  | Sorting based on polyethylene data |
| Recycling | 379.44 | g |  | Recycling based on polyethylene data |
| Polypropylene (retrieved from recycling) | -341.49 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Incinerating | 683.53 | g | Zampori \& Pant, 2019 |  |
| Electricity (retrieved from polypropylene) | -5.51 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of polypropylene is $40.34 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from polypropylene) | -6.34 | MJ | RVO, 2020; TNO, 2021 |  |
| Disposal | 42.28 | g | Zampori \& Pant, 2019 |  |
|  |  |  |  |  |
| Single-use AL box |  |  |  | Values recalculated to 1.1 L volume and 43 units |
| Recycling aluminium | 397.57 | g | ecoinvent, 2019 | Sorting already included for aluminium recycling |
| Aluminium (recovered from recycling) | -397.57 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Recycling paper | 316.19 | g | ecoinvent, 2019 | Sorting already included for paper recycling |
| Paper (recovered from recycling) | -268.76 | g | Van Veizen et al., 2019 | Credits from End-of-Life |
| Sorting polyethylene | 3.61 | g | ecoinvent, 2019 |  |
| Recycling polyethylene | 3.61 | g | ecoinvent, 2019 |  |
| Polyethylene (recovered from recycling) | -3.25 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Incinerating paper | 45.83 | g | Zampori \& Pant, 2019 |  |
| Incinerating polyethylene | 6.51 | g | Zampori \& Pant, 2019 |  |
| Electricity (retrieved from paper) | -0.19 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of paper is $20.70 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from paper) | -0.22 | MJ | RVO, 2020; TNO, 2021 |  |
| Electricity (retrieved from polyethylene) | -0.052 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of polyethylene is $39.93 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from polyethylene) | -0.050 | MJ | RVO, 2020; TNO, 2021 |  |
| Disposal aluminium | 26.19 | g | Zampori \& Pant, 2019 |  |
| Disposal paper | 1.77 | g | Zampori \& Pant, 2019 |  |
| Disposal polyethylene | 0.40 | g | Zampori \& Pant, 2019 |  |
|  |  |  |  |  |
| Single-use PA box |  |  |  | Values recalculated to 43 units |
| Recycling paper | 761.81 | g | ecoinvent, 2019 | Sorting already included for paper recycling |
| Paper (recovered from recycling) | -647.54 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Sorting polyethylene | 8.71 | g | ecoinvent, 2019 |  |
| Recycling polyethylene | 8.71 | g | ecoinvent, 2019 |  |
| PE (recovered from recycling) | -7.84 | g | Van Velzen et al., 2019 | Credits from End-of-Life |
| Incinerating paper | 110.42 | g | Zampori \& Pant, 2019 |  |
| Incinerating polyethylene | 15.68 | g | Zampori \& Pant, 2019 |  |
| Electricity (retrieved from paper) | -0.56 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of paper is $20.70 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from paper) | -0.53 | MJ | RVO, 2020; TNO, 2021 |  |
| Electricity (retrieved from polyethylene) | -0.13 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating value of polyethylene is $39.93 \mathrm{MJ} / \mathrm{kg}$ |
| Heat (retrieved from polyethylene) | -0.14 | MJ | RVO, 2020; TNO, 2021 |  |
| Disposal paper | 4.27 | g | Zampori \& Pant, 2019 |  |
| Disposal polyethylene | 0.97 |  | Zampori \& Pant, 2019 |  |

### 4.3 Contribution and dominance analyses

In order to be able to perform contribution and dominance analyses, two initial models were composed in SimaPro using readily available data. The model representative for the life cycle of a reusable meal container system was based on the reusable PP box. The system configurations included were based on those identified as the worst-case scenarios (i.e. resulting in the highest environmental impacts) in section 4.2. These are: handwashing for the Customer cleaning stage, scenario 1b for the Retrieval and redistribution stage and conventional dishwashing for the Professional cleaning stage. The model representative for the life cycle of a single-use meal container system was based on the single-use PP box. By considering the same material for both containers, it was expected that the calculations would result in the most reliable results in terms of comparability. The potential difference in impacts could then be attributed to the differences between the reusable and single-use product systems, rather than being dominated by the fact that the meal containers consist of two different material types.

Table 18: Environmental impacts per impact category of the life cycle stages of the initial reusable model. Absolute values and the percentual contributions to the total impacts are indicated. A distinction was made between the impacts and credits resulting from the End-of-Life stage. Orange indicates that a stage is dominant, green indicates that it is not.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO 2 eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Total | $1.07 \mathrm{E}+02$ | $6.07 \mathrm{E}+00$ | $5.96 \mathrm{E}-07$ | $8.21 \mathrm{E}-03$ | $2.18 \mathrm{E}-02$ | $1.74 \mathrm{E}-02$ | $2.08 \mathrm{E}+00$ |
| Material production | $1.47 \mathrm{E}+01$ | $4.18 \mathrm{E}-01$ | $2.73 \mathrm{E}-08$ | $8.73 \mathrm{E}-05$ | $1.49 \mathrm{E}-03$ | $3.85 \mathrm{E}-04$ | $1.98 \mathrm{E}-01$ |
| $\uparrow$ in \% to total | 14\% | 7\% | 5\% | 1\% | 7\% | 2\% | 9\% |
| Manufacturing | $2.78 \mathrm{E}+00$ | $1.84 \mathrm{E}-01$ | 9.52E-09 | $3.26 \mathrm{E}-05$ | 7.61E-04 | 4.53E-04 | $2.91 \mathrm{E}-02$ |
| $\uparrow$ in \% to total | 3\% | 3\% | 2\% | 0\% | 3\% | 3\% | 1\% |
| Distribution | $1.60 \mathrm{E}+00$ | 9.32E-02 | $1.04 \mathrm{E}-08$ | $4.02 \mathrm{E}-05$ | $1.33 \mathrm{E}-03$ | $2.33 \mathrm{E}-04$ | $3.60 \mathrm{E}-02$ |
| $\uparrow$ in \% to total | 1\% | 2\% | 2\% | 0\% | 6\% | 1\% | 2\% |
| Customer cleaning | $4.43 \mathrm{E}+01$ | $2.58 \mathrm{E}+00$ | $1.97 \mathrm{E}-07$ | $6.68 \mathrm{E}-04$ | 8.31E-03 | $1.08 \mathrm{E}-02$ | $1.38 \mathrm{E}+00$ |
| $\uparrow$ in \% to total | 41\% | 42\% | 33\% | 8\% | 38\% | 62\% | 66\% |
| Retrieval and redistribution | $2.86 \mathrm{E}+01$ | $2.02 \mathrm{E}+00$ | $2.76 \mathrm{E}-07$ | $7.22 \mathrm{E}-03$ | $6.74 \mathrm{E}-03$ | $1.72 \mathrm{E}-03$ | $1.27 \mathrm{E}-01$ |
| $\uparrow$ in \% to total | 27\% | 33\% | 46\% | 88\% | 31\% | 10\% | 6\% |
| Professional cleaning | $1.81 \mathrm{E}+01$ | 7.61E-01 | $8.02 \mathrm{E}-08$ | $1.81 \mathrm{E}-04$ | 3.64E-03 | 3.88E-03 | $3.37 \mathrm{E}-01$ |
| $\uparrow$ in \% to total | 17\% | 13\% | 13\% | 2\% | 17\% | 22\% | 16\% |
| End-of-Life impacts | $4.76 \mathrm{E}-01$ | $1.85 \mathrm{E}-01$ | 2.76E-09 | $6.26 \mathrm{E}-06$ | $1.11 \mathrm{E}-04$ | $1.23 \mathrm{E}-04$ | $6.00 \mathrm{E}-03$ |
| $\uparrow$ in \% to total | 0\% | $3 \%$ | 0\% | 0\% | 1\% | 1\% | 0\% |
| End-of-Life credits | $-3.79 \mathrm{E}+00$ | -1.70E-01 | -6.46E-09 | -2.87E-05 | -5.89E-04 | -2.34E-04 | -3.43E-02 |
| $\uparrow$ in \% to total | -4\% | -3\% | -1\% | 0\% | -3\% | -1\% | -2\% |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use
The environmental impacts resulting from the reusable system were assessed and contribution and dominance analyses were applied to determine which life cycle stages are significantly influential. A stage was considered dominant if it contributed for at least $10 \%$ of the total impact for at least four impact categories. Table 18 provides an overview of the resulting impacts from the life cycle stages of the reusable system. Absolute values are indicated and the percentual contribution of those to the total impact for each impact category are provided below them. The impacts for the EoL stage were divided into positive values and negative values, to provide a clear overview of the credits that are attributed as a result of recovering materials and energy from the recycling and incineration with energy recovery processes. It can be observed from the table that the life cycle stages Customer cleaning, Retrieval and redistribution, and Professional cleaning are considered dominant. Thus, additional data had to be collected to establish uncertainty ranges for these life cycle stages. The highest impacts for the majority of the impact categories result from the Customer cleaning stage (handwashing the container).

Table 19: Environmental impacts per impact category of the life cycle stages of the initial single-use model. Absolute values and the percentual contributions to the total impacts are indicated. A distinction was made between the impacts and credits resulting from the End-of-Life stage. Orange indicates that a stage is dominant, green indicates that it is not.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO 2 eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | kg SO 2 eq | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Total | $1.88 \mathrm{E}+02$ | $8.24 \mathrm{E}+00$ | $2.76 \mathrm{E}-07$ | $1.54 \mathrm{E}-03$ | $3.45 \mathrm{E}-02$ | $1.08 \mathrm{E}-02$ | $2.25 \mathrm{E}+00$ |
| Material production | $1.82 \mathrm{E}+02$ | $5.02 \mathrm{E}+00$ | $9.71 \mathrm{E}-08$ | $1.03 \mathrm{E}-03$ | $1.77 \mathrm{E}-02$ | $4.45 \mathrm{E}-03$ | $2.05 \mathrm{E}+00$ |
| $\uparrow$ in \% to total | 97\% | 61\% | 35\% | 67\% | 51\% | 41\% | 91\% |
| Manufacturing | $3.60 \mathrm{E}+01$ | $2.38 \mathrm{E}+00$ | $1.23 \mathrm{E}-07$ | $4.21 \mathrm{E}-04$ | $9.84 \mathrm{E}-03$ | $5.86 \mathrm{E}-03$ | $3.76 \mathrm{E}-01$ |
| $\uparrow$ in \% to total | 19\% | 29\% | 45\% | 27\% | 28\% | 54\% | 17\% |
| Distribution | $1.28 \mathrm{E}+01$ | $7.84 \mathrm{E}-01$ | $1.03 \mathrm{E}-07$ | $3.77 \mathrm{E}-04$ | 1.31E-02 | $1.91 \mathrm{E}-03$ | $1.93 \mathrm{E}-01$ |
| $\uparrow$ in \% to total | 7\% | 10\% | 37\% | 25\% | 38\% | 18\% | 9\% |
| End-of-Life impacts | $6.13 \mathrm{E}+00$ | $2.22 \mathrm{E}+00$ | $3.55 \mathrm{E}-08$ | $8.05 \mathrm{E}-05$ | $1.41 \mathrm{E}-03$ | $1.55 \mathrm{E}-03$ | 7.74E-02 |
| $\uparrow$ in \% to total | 3\% | 27\% | 13\% | 5\% | 4\% | 14\% | 3\% |
| End-of-Life credits | $-4.85 \mathrm{E}+01$ | $-2.16 \mathrm{E}+00$ | -8.20E-08 | -3.67E-04 | -7.51E-03 | -2.97E-03 | -4.41E-01 |
| $\uparrow$ in \% to total | -26\% | -26\% | -30\% | -24\% | -22\% | -28\% | -20\% |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use

The environmental impacts resulting from the single-use system were also assessed and contribution and dominance analyses were applied. Because this system consists of fewer life cycle stages, a standard of at least $17.5 \%$ was applied instead of the $10 \%$ for the reusable system. Table 19 provides an overview of the resulting impacts from the life cycle stages of the single-use system. Again, absolute values are indicated and the percentual contribution of those to the total impact for each impact category are provided below them. The impacts for the EoL stage have also been divided into positive values and negative values. Surprisingly, it can be observed from the table that all life cycle stages are considered dominant. Even the impacts from the Distribution stage attribute for at least $17.5 \%$ to four of the seven impact categories. Thus, additional data had to be collected to establish uncertainty ranges for all life cycle stages. The highest impacts for the majority of the impact categories result from the Material production stage.

### 4.4 Uncertainty analysis for the dominant life cycle stages

After identifying the dominant life cycle stages, additional data were collected to establish uncertainty ranges for the different system configurations of those stages. To ensure improved readability throughout the report, the uncertainty ranges of the input data established in this section were already included in the data tables in section 4.2. The impact assessments of the different options for the life cycle stages for which multiple system configurations are possible were conducted using the average values of the uncertainty ranges for the component that was expected to contribute most to the total impact of an option.

Because of time constraints, it was decided not to collect additional data to establish uncertainty ranges for the input data for specific processes of all life cycle stages. The contribution and dominance analyses indicated that for a single-use meal container system all stages are considered dominant. However, for the reusable meal container system, none of those stages (Material production, Manufacturing, Distribution and EoL) are considered dominant. Therefore, it was decided to only collect additional data for the three dominant stages of the reusable meal container system, namely Customer cleaning, Retrieval and redistribution, and Professional cleaning.

### 4.4.1 Uncertainty Customer cleaning stage

For the Customer cleaning stage, it was expected that the energy used during handwashing and dishwashing would be the main contributing process to the total resulting impacts from these options. Additional data were therefore collected based on more modern appliances that use less energy for the same function because of higher efficiencies as a result of technological improvements.

The natural gas boiler data obtained from research by Potting \& Van der Harst (2015) was based on a boiler efficiency of $85 \%$. Research by Vakkilainen (2016) indicated that the efficiency of a modern natural gas boiler can range up to $94 \%$. Applying this efficiency would result in an energy use of 0.4 MJ per 1.1L volume container instead of 0.44 MJ . Therefore, the average 0.42 MJ was considered in this research.

The energy use of the dishwasher data obtained from research by Potting \& Van der Harst (2015) was expected to be 1.0 kWh per wash. Data obtained from the website of Bosch (2020) indicated that modern dishwashers use 0.8 kWh per wash on average. Therefore, the average of 0.9 kWh (which equals 3.24 MJ) per dishwasher load was considered in this research.

For the options dry wiping and cold water rinsing, additional data sources were not encountered during this research. Therefore, the uncertainty ranges were established based on lower or higher amounts that can potentially be used during these options. Different types of meals can leave different amounts of food residue and customer behaviour can influence the amount of resources required for cleaning too. For dry wiping, it was expected that three paper towels could also be sufficient, but several customers might use five paper towels for dry wiping one 1.1 L volume meal container. Based on this, the uncertainty range of $6-10 \mathrm{~g}$ per container was established and the average of 8 g was included in the assessments. For cold water rinsing, it was expected that the same amount of water as required for one dirty dinner plate could be sufficient, but twice that amount could also be possible. Thus, the uncertainty range of 1.18-2.36 L per container was established and the average of 1.77 L was included in the assessments.

### 4.4.2 Uncertainty Retrieval and redistribution stage

For the electric bicycle, the uncertainty range was based on two types of electric bicycles (one standard and one electricity label-certified) with different electricity use efficiencies. The ecoinvent datasets for electric bicycles were checked for representativeness regarding electric bicycles used in Belgium and the Netherlands for food delivery. No clear indications that the datasets would not be representative were encountered.

For the scooter, the dataset available in ecoinvent was not representative for scooters that are used for food delivery in Belgium and the Netherlands. The dataset consists of average values for scooters from $50-150$ cc types and delivery scooters are almost always 50 cc types (Scooterstore, 2016; SYM, n.d.). The dataset was copied and adjusted to be representative for 50 cc scooters based on different fuel consumptions. The uncertainty range was established according to differences in fuel consumption efficiencies of 50 cc scooters specifically. The majority of these types of scooters have a fuel consumption ranging from $1.96-3.36 \mathrm{~L}$ per 100 km (Licino, 2015). Thus, the average value of this range was used to adjust the ecoinvent dataset (which includes a fuel consumption of 3.5 L per 100 km ) accordingly. From this, an ecoinvent dataset expected to be representative for average 50 cc scooters specifically was obtained.

For the van, the dataset for a light commercial vehicle in ecoinvent was expected to be representative for the average type of van used in Belgium and the Netherlands. However, the problem encountered was that the unit for this is provided in tkm and the unit km cannot be selected for this dataset. Because
it was expected that the volume of the meal containers will limit the carrying capacity of the light commercial vehicle instead of the weight, and because relatively short transportation distances are required, it was decided that including the amount of tkm in the calculations would not be accurate. Therefore, an ecoinvent dataset had to be adjusted to be representative for a van with the unit km . It was decided to base this on the EU emission reduction targets for vans and passenger cars (ICCT, 2014). The only way to obtain a dataset representative for a van with the unit km, was to adjust another dataset that already included this specific unit. Because vans run on diesel, the dataset for a diesel passenger car (medium size) was adjusted. For new passenger cars, an average emission target of $130 \mathrm{~g} \mathrm{CO} 2 / \mathrm{km}$ applied between 2015 and 2019, which corresponds with 4.9 L per 100 km fuel consumption (European Commission, 2017a). For new vans, an average emission target of $175 \mathrm{~g} \mathrm{CO} 2 / \mathrm{km}$ applied between 2017 and 2019, which corresponds with 6.6 L per 100 km fuel consumption (European Commission, 2017b). Additionally, an average emission target of $147 \mathrm{~g} \mathrm{CO} 2 / \mathrm{km}$ applies from 2020 onward, corresponding with 5.6 L per 100 km diesel fuel consumption (ICCT, 2014). This range (5.6-6.6 L per 100 km ) was taken as the uncertainty range and the average value was used to adjust the dataset for a diesel passenger car to be representative for a van accordingly.

### 4.4.3 Uncertainty Professional cleaning stage

As was the case for the Customer cleaning stage, it was also expected for the Professional cleaning stage that the energy used during the different dishwashing options would be the main contributing process to the total resulting impacts. The uncertainty range for the conventional dishwashing was included similarly as for the dishwashing option included for the Customer cleaning stage.

The uncertainty ranges for the electricity use of the professional and industrial dishwashing were based on differences in the load factors encountered in research by Carbotech (2014) and research by Harnoto (2013). Electricity use values for washing products of different volumes and shapes were encountered. Because reusable meal containers can also consist of different volumes and shapes, it was expected that establishing the uncertainty ranges based on those different electricity use values would be appropriate. For professional dishwashing, the values were recalculated to the unit MJ for a 1.1 L volume container and range from 0.053 to 0.11 . Therefore, an average of 0.082 MJ per 1.1 L volume container was considered in this research. For industrial dishwashing, the values were also recalculated to the unit MJ for a 1.1 L volume container and range from 0.029 to 0.035 . Therefore, an average of 0.032 MJ per 1.1 L volume container was considered in this research.

### 4.5 Life cycle impacts of meal container systems

In this section, the resulting impacts from the complete life cycles of the reusable and single-use meal container systems considered in this research were assessed. First, the impacts from the three reusable boxes were assessed and compared with each other. Then, the impacts from the three single-use boxes were assessed and compared with each other. Thereafter, the impacts from all six boxes were compared with each other, to obtain a clear overview of the differences between the reusables and single-use ones. Finally, three different sensitivity analyses were performed and the resulting impacts were again assessed in order to identify what the effects to the obtained results were.

### 4.5.1 Life cycle impacts of reusable boxes

From consulting with multiple different types of organisations within the food delivery and take-away industry sector, the most realistic life cycle configurations for reusable meal container systems were identified. For the Customer cleaning stage, this is the option of applying cold water rinsing. For the Retrieval and redistribution stage, it is most common that organisations working with reusable meal containers make use of at-home/at-restaurant exchanges, to avoid additional environmental impacts during this process. For the Professional cleaning stage, most organisations indicated that the containers
are cleaned with a professional dishwasher at the restaurants. The life cycles of the three reusable boxes were thus modelled taken these system configurations into account.


Figure 16: Relative environmental impacts per impact category for each of the three reusable boxes considered in this research. Error bars were added to indicate the uncertainty ranges.

Figure 16 illustrates how the environmental impacts resulting from the complete life cycles of the three reusable boxes compare with each other. The uncertainty ranges were included and are indicated by the error bars. It can be observed from the figure that the reusable SS box results in the lowest environmental impacts for all impact categories and the reusable GL box in the highest. The findings thus indicate that the reusable SS box is the environmentally preferred option of the three. This can mainly be attributed to the fact that steel is a durable material and that the box can be used 200 times on average because of that. However, it has to be noted that using a reusable meal container 200 times in practice might prove difficult because this is influenced by the return rate. This is explained in more detail in section 4.6. The reusable GL box is the least environmentally preferred option, although for the impact categories CED, EP and WU, the differences impacts in respect to those from the reusable PP box are small. Nevertheless, when compared with the reusable SS box, the reusable GL box results in more than twice the environmental impacts for the impact categories CED (48\%), GW (45\%), PO ( $46 \%$ ) and AP ( $41 \%$ ).

Table 20: Absolute values of the environmental impacts per impact category of the life cycle stages of the reusable boxes considered in this research. A distinction was made between the impacts and credits resulting
from the End-of-Life stage.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO 2 eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}{ }_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Reusable PP box | $2.90 \mathrm{E}+01$ | $1.29 \mathrm{E}+00$ | $1.50 \mathrm{E}-07$ | $2.62 \mathrm{E}-04$ | $6.13 \mathrm{E}-03$ | $3.96 \mathrm{E}-03$ | 5.98E-01 |
| Material production | $1.47 \mathrm{E}+01$ | $4.18 \mathrm{E}-01$ | $2.73 \mathrm{E}-08$ | $8.73 \mathrm{E}-05$ | $1.49 \mathrm{E}-03$ | $3.85 \mathrm{E}-04$ | $1.98 \mathrm{E}-01$ |
| Manufacturing | $2.78 \mathrm{E}+00$ | $1.84 \mathrm{E}-01$ | $9.52 \mathrm{E}-09$ | $3.26 \mathrm{E}-05$ | 7.61E-04 | $4.53 \mathrm{E}-04$ | $2.91 \mathrm{E}-02$ |
| Distribution | $1.60 \mathrm{E}+00$ | 9.32E-02 | $1.04 \mathrm{E}-08$ | $4.02 \mathrm{E}-05$ | $1.33 \mathrm{E}-03$ | $2.33 \mathrm{E}-04$ | $3.60 \mathrm{E}-02$ |
| Customer cleaning | $1.03 \mathrm{E}+00$ | $6.22 \mathrm{E}-02$ | $5.89 \mathrm{E}-09$ | $2.08 \mathrm{E}-05$ | 4.42E-04 | $1.09 \mathrm{E}-03$ | $1.43 \mathrm{E}-01$ |
| Retrieval and redistribution | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ |
| Professional cleaning | $1.22 \mathrm{E}+01$ | $5.15 \mathrm{E}-01$ | $1.01 \mathrm{E}-07$ | $1.04 \mathrm{E}-04$ | $2.58 \mathrm{E}-03$ | $1.91 \mathrm{E}-03$ | $2.21 \mathrm{E}-01$ |
| End-of-Life impacts | $4.76 \mathrm{E}-01$ | $1.85 \mathrm{E}-01$ | $2.76 \mathrm{E}-09$ | $6.26 \mathrm{E}-06$ | $1.11 \mathrm{E}-04$ | $1.23 \mathrm{E}-04$ | $6.00 \mathrm{E}-03$ |
| End-of-Life credits | $-3.79 \mathrm{E}+00$ | -1.70E-01 | -6.46E-09 | -2.87E-05 | -5.89E-04 | -2.34E-04 | $-3.43 \mathrm{E}-02$ |
| Reusable SS box | $1.57 \mathrm{E}+01$ | $7.44 \mathrm{E}-01$ | $1.19 \mathrm{E}-07$ | $1.82 \mathrm{E}-04$ | $4.18 \mathrm{E}-03$ | $3.39 \mathrm{E}-03$ | $4.15 \mathrm{E}-01$ |
| Material production | $4.50 \mathrm{E}+00$ | $3.07 \mathrm{E}-01$ | $1.49 \mathrm{E}-08$ | $1.07 \mathrm{E}-04$ | $1.70 \mathrm{E}-03$ | $5.58 \mathrm{E}-04$ | $4.23 \mathrm{E}-02$ |
| Manufacturing | $1.05 \mathrm{E}+00$ | 7.96E-02 | $4.68 \mathrm{E}-09$ | $2.38 \mathrm{E}-05$ | $3.45 \mathrm{E}-04$ | $1.99 \mathrm{E}-04$ | $3.54 \mathrm{E}-02$ |
| Distribution | $4.91 \mathrm{E}-01$ | 3.04E-02 | $3.95 \mathrm{E}-09$ | $1.46 \mathrm{E}-05$ | $5.08 \mathrm{E}-04$ | $7.55 \mathrm{E}-05$ | $8.01 \mathrm{E}-03$ |
| Customer cleaning | $1.03 \mathrm{E}+00$ | $6.22 \mathrm{E}-02$ | $5.89 \mathrm{E}-09$ | $2.08 \mathrm{E}-05$ | $4.42 \mathrm{E}-04$ | $1.09 \mathrm{E}-03$ | $1.43 \mathrm{E}-01$ |
| Retrieval and redistribution | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ |
| Professional cleaning | $1.22 \mathrm{E}+01$ | $5.15 \mathrm{E}-01$ | $1.01 \mathrm{E}-07$ | $1.04 \mathrm{E}-04$ | $2.58 \mathrm{E}-03$ | $1.91 \mathrm{E}-03$ | $2.21 \mathrm{E}-01$ |
| End-of-Life impacts | $2.63 \mathrm{E}-01$ | $1.49 \mathrm{E}-02$ | $1.27 \mathrm{E}-09$ | $4.88 \mathrm{E}-06$ | 7.54E-05 | $3.96 \mathrm{E}-05$ | $1.91 \mathrm{E}-03$ |
| End-of-Life credits | $-3.87 \mathrm{E}+00$ | -2.65E-01 | -1.28E-08 | -9.23E-05 | -1.46E-03 | -4.80E-04 | -3.66E-02 |
| Reusable GL box | $3.21 \mathrm{E}+01$ | $1.65 \mathrm{E}+00$ | $2.03 \mathrm{E}-07$ | $3.94 \mathrm{E}-04$ | $1.02 \mathrm{E}-02$ | $4.37 \mathrm{E}-03$ | $6.07 \mathrm{E}-01$ |
| Material production | $1.40 \mathrm{E}+01$ | $6.61 \mathrm{E}-01$ | $6.89 \mathrm{E}-08$ | $1.76 \mathrm{E}-04$ | $4.20 \mathrm{E}-03$ | $7.42 \mathrm{E}-04$ | $1.96 \mathrm{E}-01$ |
| Manufacturing | $6.21 \mathrm{E}+00$ | $4.29 \mathrm{E}-01$ | $2.84 \mathrm{E}-08$ | $6.82 \mathrm{E}-05$ | $1.58 \mathrm{E}-03$ | $4.11 \mathrm{E}-04$ | $4.31 \mathrm{E}-02$ |
| Distribution | $4.43 \mathrm{E}+00$ | $2.45 \mathrm{E}-01$ | $2.88 \mathrm{E}-08$ | $1.11 \mathrm{E}-04$ | $3.69 \mathrm{E}-03$ | $5.68 \mathrm{E}-04$ | $7.22 \mathrm{E}-02$ |
| Customer cleaning | $1.03 \mathrm{E}+00$ | $6.22 \mathrm{E}-02$ | $5.89 \mathrm{E}-09$ | $2.08 \mathrm{E}-05$ | $4.42 \mathrm{E}-04$ | $1.09 \mathrm{E}-03$ | $1.43 \mathrm{E}-01$ |
| Retrieval and redistribution | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ | $0.00 \mathrm{E}+00$ |
| Professional cleaning | $1.22 \mathrm{E}+01$ | $5.15 \mathrm{E}-01$ | $1.01 \mathrm{E}-07$ | $1.04 \mathrm{E}-04$ | $2.58 \mathrm{E}-03$ | $1.91 \mathrm{E}-03$ | $2.21 \mathrm{E}-01$ |
| End-of-Life impacts | $3.27 \mathrm{E}-01$ | $9.48 \mathrm{E}-02$ | $2.32 \mathrm{E}-09$ | $7.14 \mathrm{E}-06$ | $8.17 \mathrm{E}-05$ | $8.10 \mathrm{E}-05$ | $3.31 \mathrm{E}-03$ |
| End-of-Life credits | $-6.12 \mathrm{E}+00$ | -3.55E-01 | -3.21E-08 | -9.34E-05 | -2.36E-03 | -4.37E-04 | -7.12E-02 |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use
Table 20 contains absolute values of the resulting environmental impacts from the life cycle stages of the three reusable boxes. A distinction was made between the impacts and credits resulting from the EoL stage. From the table, it can be observed that the relatively low impacts from the reusable SS box can also partly be attributed to the high recycling percentage (and associated value retention) for steel. The credits received from avoided virgin steel production in a subsequent product life cycle compensate for the impacts resulting from the life cycle stage Material production for a large part for all impact categories. For the impact category CED for instance, 4.5 MJ is required for producing the materials for the reusable SS box according to the FU , whilst 3.87 MJ is retrieved during the EoL stage and attributed as credits to the product system. The findings also indicate that the Professional cleaning stage contributes most to the total impacts of the complete life cycles of the reusable PP and SS boxes for the majority of the impact categories. For the reusable GL box, the Material production stage contributes most. In Appendix D, stacked bar plot figures were included to provide a clear overview of the percentual contributions from the different life cycle stages of the three reusable meal container systems to the total impact for each impact category.

### 4.5.2 Life cycle impacts of single-use boxes

For the single-use boxes considered in this research, no real different life cycle system configurations can be applied. It can thus be expected that the resulting impacts assessed in this section will always remain the same, although it is important to note that these results are region-specific.


Figure 17: Relative environmental impacts per impact category for each of the three single-use boxes considered in this research.

Figure 17 illustrates how the environmental impacts resulting from the complete life cycles of the three single-use boxes compare with each other. It can be observed that the single-use PP box results in the highest impacts for all impact categories. The findings thus indicate that the this box is the least environmentally preferred option of the three. A potential explanation for this is that the single-use PP box weighs the most of the three single-use boxes considered in this research and thus more material is required for the production. However, it also has to be taken into account that the environmental impacts differ per material type. The resulting impacts from the single-use AL and PA boxes are relatively close for the majority of the impact categories. The single-use PA box results in the lowest impacts for four of the seven impact categories, although the difference with the single-use AL box for the impact category GW is small. Nevertheless, the single-use AL box results in the lowest impacts for the impact categories CED, AP and WU. It is therefore difficult to conclude which of these two boxes would be the most environmentally preferred option because this also depends on the impact categories that are deemed most important for specific situations.

Table 21: Absolute values of the environmental impacts per impact category of the life cycle stages of the singleuse boxes considered in this research. A distinction was made between the impacts and credits resulting from the

End-of-Life stage.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | $\mathrm{kg} \mathrm{CO}_{2} \mathrm{eq}$ | kg CFC-11 eq | $\mathrm{kg} \mathrm{C}_{2} \mathrm{H}_{4} \mathrm{eq}$ | kg SO2 eq | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ |  |
| Single-use PP box | $1.88 \mathrm{E}+02$ | $8.24 \mathrm{E}+00$ | $2.76 \mathrm{E}-07$ | $1.54 \mathrm{E}-03$ | $3.45 \mathrm{E}-02$ | $1.08 \mathrm{E}-02$ | $2.25 \mathrm{E}+00$ |
| Material production | $1.82 \mathrm{E}+02$ | $5.02 \mathrm{E}+00$ | $9.71 \mathrm{E}-08$ | $1.03 \mathrm{E}-03$ | $1.77 \mathrm{E}-02$ | $4.45 \mathrm{E}-03$ | $2.05 \mathrm{E}+00$ |
| Manufacturing | 3.60 E | $2.38 \mathrm{E}+00$ | 1. | 4. | $9.84 \mathrm{E}-03$ | $5.86 \mathrm{E}-03$ | $3.76 \mathrm{E}-01$ |
| Distribution | $1.28 \mathrm{E}+01$ | $7.84 \mathrm{E}-01$ | 1.03 | $3.77 \mathrm{E}-04$ | $1.31 \mathrm{E}-02$ | $1.91 \mathrm{E}-03$ | 1.93E-01 |
| End-of-Life impacts | $6.13 \mathrm{E}+0$ | $2.22 \mathrm{E}+00$ | $3.55 \mathrm{E}-0$ | $8.05 \mathrm{E}-05$ | $1.41 \mathrm{E}-03$ | $1.55 \mathrm{E}-03$ | 7.74E-02 |
| End-of-Life credits | $-4.85 \mathrm{E}+01$ | $-2.16 \mathrm{E}+00$ | -8.20E-08 | -3.67E-04 | $-7.51 \mathrm{E}-03$ | -2.97E-03 | -4. |
| Single-use AL box | $6.54 \mathrm{E}+0$ | $4.17 \mathrm{E}+00$ | $2.41 \mathrm{E}-0$ | $1.29 \mathrm{E}-03$ | $2.55 \mathrm{E}-02$ | $7.93 \mathrm{E}-03$ | $1.51 \mathrm{E}+00$ |
| Material produc | $1.33 \mathrm{E}+02$ | $1.01 \mathrm{E}+01$ | 3.50 | $3.50 \mathrm{E}-03$ | $5.69 \mathrm{E}-02$ | $1.53 \mathrm{E}-02$ | 2. |
| Manufacturing | 1.31 E | $9.15 \mathrm{E}-01$ | $5.07 \mathrm{E}-08$ | $2.11 \mathrm{E}-04$ | $3.61 \mathrm{E}-03$ | $1.91 \mathrm{E}-03$ | $1.75 \mathrm{E}-01$ |
| Distribution | 7.26 E | $4.29 \mathrm{E}-01$ | 5.18 | 1.95 | $6.62 \mathrm{E}-03$ | $1.05 \mathrm{E}-03$ | 1 |
| End-of-Life impact | 1.19 E | $6.35 \mathrm{E}-01$ | $5.68 \mathrm{E}-0$ | $1.25 \mathrm{E}-04$ | $2.84 \mathrm{E}-03$ | $1.53 \mathrm{E}-03$ | $5.42 \mathrm{E}-01$ |
| End-of-Life credits | $-1.00 \mathrm{E}+02$ | $-7.88 \mathrm{E}+00$ | -2.69E-07 | -2.74E-03 | $-4.45 \mathrm{E}-02$ | -1.19E-02 | $-1.53 \mathrm{E}+00$ |
| Single-use PA box | $7.88 \mathrm{E}+0$ | $4.14 \mathrm{E}+00$ | $2.16 \mathrm{E}-0$ | $9.95 \mathrm{E}-04$ | $2.76 \mathrm{E}-02$ | $7.09 \mathrm{E}-03$ | $1.76 \mathrm{E}+00$ |
| Material production | $6.53 \mathrm{E}+01$ | $1.32 \mathrm{E}+00$ | $1.13 \mathrm{E}-07$ | $3.83 \mathrm{E}-04$ | $7.45 \mathrm{E}-03$ | .42E-03 | $2.23 \mathrm{E}+00$ |
| Manufacturin | $2.54 \mathrm{E}+01$ | $2.39 \mathrm{E}+00$ | $1.71 \mathrm{E}-08$ | $3.97 \mathrm{E}-04$ | $1.07 \mathrm{E}-02$ | $2.35 \mathrm{E}-03$ | $2.57 \mathrm{E}-01$ |
| Distribution | $1.03 \mathrm{E}+01$ | $6.38 \mathrm{E}-01$ | $8.62 \mathrm{E}-08$ | $3.13 \mathrm{E}-04$ | $1.10 \mathrm{E}-02$ | $1.56 \mathrm{E}-03$ | $1.40 \mathrm{E}-01$ |
| End-of-Life impacts | $1.75 \mathrm{E}+01$ | $6.64 \mathrm{E}-01$ | $7.24 \mathrm{E}-08$ | $1.36 \mathrm{E}-04$ | $3.17 \mathrm{E}-03$ | $1.99 \mathrm{E}-03$ | $4.73 \mathrm{E}-01$ |
| End-of-Life credits | $-3.96 \mathrm{E}+01$ | -8.77E-01 | -7.30E-08 | -2.35E-04 | -4.75E-03 | -2.22E-03 | $-1.34 \mathrm{E}+00$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use
Table 21 contains absolute values of the resulting environmental impacts from the life cycle stages of the three single-use boxes. Again, a distinction is made between the impacts and credits resulting from the EoL stage. From the table, it can be observed that the relatively high impacts of the single-use PP box can partly be attributed to the fact that the recycling percentages for plastic materials are low in comparison to those for other materials. The credits received from the avoided virgin material production during the EoL stage of the single-use AL and PA boxes account for a larger share of the total impacts for the majority of impact categories than is the case for the single-use PP box. Additionally, the findings indicate that for all three single-use boxes, the impacts resulting from the Material production stage contribute for the majority to the total impacts resulting from the complete life cycles for almost all impact categories. In Appendix D, stacked bar plot figures were included to provide a clear overview of the percentual contributions from the different life cycle stages of the three single-use meal container systems to the total impact for each impact category.

### 4.5.3 Comparing life cycle impacts of reusable and single-use boxes

The main question of this research is how the resulting impacts from the life cycles of reusable meal container systems compare with those from single-use systems.


Figure 18: Relative environmental impacts per impact category for all meal boxes considered in this research.
Figure 18 provides an overview of how the resulting environmental impacts from the three reusable and the three single-use boxes compare with each other for each impact category. From the figure, it can be observed that all three reusable boxes with the most realistic system configurations result in lower impacts than all three single-use boxes for each of the seven impact categories. The findings thus indicate that, with the most realistic system configurations taken into account, reusable meal containers are always environmentally preferred over single-use ones for these impact categories. For the majority of the impact categories assessed in this research, the differences of the resulting impacts from the reusable boxes are large in comparison to those from the single-use boxes. The largest differences are observed when comparing the reusable SS box with the single-use PP box. For five out of the seven impact categories, the single-use PP box results in approximately 5-12 times the impact of the reusable SS box. For the impact categories EP and OLD, the impacts are more than 3 and more than 2 times higher respectively.

When comparing all meal containers with each other, for the impact category GW for instance, the resulting impacts from the single-use boxes are at least 2.5 times higher than for those from all reusable boxes. The resulting impact for this impact category from the single-use PP box are even 5-11 times higher than those from the reusable boxes. However, for the impact category OLD, the differences in impacts between reusable and single-use meal container systems are relatively small. Although the impact of the single-use PP box is still more than 2 times higher than that of the reusable SS box, when comparing the single-use PA box and the reusable GL box with each other, the impacts are close to equal. When taking the uncertainty ranges presented in section 4.5 .1 into account, it is possible that the reusable GL box even results in a higher impact than the single-use PA box for this impact category. The life cycle stage Professional cleaning from the reusable meal container systems contributes most to the total impacts for this impact category, mainly because of the use of the NaOH solution as the detergent that contains relatively high amounts of CFCs. These impacts could be reduced by using more environmentally friendly detergent types.

### 4.5.4 Sensitivity analysis of the life cycle impacts of reusable boxes

In order to assess the robustness of the results presented in section 4.5 .3 with the most realistic configurations included in the reusable systems, three sensitivity analyses were performed. After applying a sensitivity analysis and adjusting the models accordingly, the resulting impacts were assessed again. The results are presented in this section and it is discussed how these were influenced by a certain sensitivity analysis. The modelling in this section was based on CLCA, with the reusable meal container systems of section 4.5.1 taken as the baseline scenarios. In order to provide a clear overview of the changes in the impacts of the reusable boxes for each impact category, the impacts from the reusable PP box in the baseline scenario were included in all figures. Additionally, the impacts from the single-use PP box remained at $100 \%$ in all figures. It is important to note that for each sensitivity analysis, only one of the most realistic configurations was altered to the worst-case option for that life cycle stage in respect to the reusable systems analysed in the previous sections, not a combination of multiple.

For the first sensitivity analysis (referred to as sensitivity 1), the option of applying cold water rinsing during the Customer cleaning stage was replaced by the option of applying handwashing. In section 4.2.6, the results indicated that handwashing is the option for this stage that results in the highest environmental impacts for all impact categories. The impacts were significantly higher than those from the option cold water rinsing and thus the reusable systems result in higher impacts for all categories as a result of this change. It is therefore interesting to provide an overview of what the effects of this change to the results would be.


Figure 19: Relative environmental impacts per impact category after applying sensitivity 1 to the reusable meal container systems.

Figure 19 provides an overview of how the resulting environmental impacts from the reusable boxes compare with those from the single-use boxes, after applying sensitivity 1 . It can be observed from the figure that the impacts resulting from the reusable boxes have changed drastically. All three reusable boxes are still environmentally preferred over the single-use PP box for five out of the seven impact
categories. However, for the impact categories OLD and EP, it can now be observed that all reusable boxes perform worse than all single-use boxes. The impacts for the category WU of all three reusable boxes are now higher than those of the single-use AL and PA boxes, except for the reusable SS box, which is marginally lower than that of the single-use PA box. Only for the impact category AP, the findings indicate that all three reusable boxes are still environmentally preferred over all three singleuse boxes. Nevertheless, the differences in impacts for the categories CED, GW and PO when comparing the reusable boxes with the single-use AL and PA boxes are now small. The results thus indicate that is of utmost importance what method of customer cleaning is applied to reusable meal containers. If the majority of customers handwash the containers after use, this could result in certain single-use meal container systems being environmentally preferred over reusable systems, depending on the importance attributed to specific impact categories.

For the second sensitivity analysis (referred to as sensitivity 2 ), it was assumed that a retrieval round by a scooter (scenario 1b) would be required for the Retrieval and redistribution stage instead of making use of at-home/at-restaurant exchanges (scenario 3) for recollecting the reusable containers. In section 4.2.7, the results indicated that this scenario results in the highest environmental impacts for six out of the seven impact categories. Because it can be expected that in reality it might not always be possible to avoid additional impacts resulting from this life cycle stage, the models were adjusted to be able to describe what effects this would have on the results.


Figure 20: Relative environmental impacts per impact category after applying sensitivity 2 to the reusable meal container systems.

Figure 20 provides an overview of how the resulting environmental impacts from the reusable boxes compare with those from the single-use boxes, after applying sensitivity 2 . It can be observed from the figure that the impacts resulting from the reusable boxes have changed drastically again, especially for the impact category PO. The resulting impacts from the three reusable boxes for this category are now 4.8-7.6 times higher than those from all single-use boxes. Also for the impact category OLD, the resulting impacts from all reusable boxes are now higher than those from all single-use boxes (1.4-2.2 times higher). However, for the other five impact categories, the reusable boxes still perform
environmentally better than all single-use boxes, although for several categories the differences have become small. The results thus indicate that the method used for recollecting the meal container is also of high importance.

For the third sensitivity analysis (referred to as sensitivity 3), the option of using a professional dishwasher during the Professional cleaning stage is replaced by the option of using a conventional dishwasher. In section 4.2 .8 , the results indicated that conventional dishwashing is the option for this stage that results in the highest environmental impacts for six out of the seven impact categories. Because it is a possibility that certain restaurants will only have a conventional dishwasher to their availability to clean the reusable containers, the effects of this change are important to analyse.


Figure 21: Relative environmental impacts per impact category after applying sensitivity 3 to the reusable meal container systems.

Figure 21 provides an overview of how the resulting environmental impacts from the reusable boxes compare with those from the single-use boxes, after applying sensitivity 3. It can be observed from the figure that the impacts resulting from the complete life cycles of the reusable boxes have not changed much. For the majority of the impact categories, the resulting impacts from the three reusable boxes are now higher, but the increases are relatively small. However, for the impact category OLD, the resulting impacts from the reusable boxes are now lower. Noticeably, reusable meal container systems perform environmentally better than single-use systems for all impact categories, even when a conventional dishwasher is used during the Professional cleaning stage. Nevertheless, it is important to remember that the findings in section 4.5.1 indicated that the Professional cleaning stage is the major contributor to the total impacts from the complete life cycles of most reusable meal container systems. Therefore, the results indicate that the professional cleaning method that is applied to reusable meal containers is important, although it appears to be of less importance than the customer cleaning method and the method used for recollecting the containers.

### 4.6 Environmental break-even points and return rate scenarios

In order to obtain a clear overview of when a reusable meal container system is environmentally preferred over a single-use one for a certain impact category, break-even point analysis was performed. The environmental break-even point in this case represents the threshold of the minimal number of uses of a reusable meal container required to result in a lower impact than when a single-use meal container would be used instead. For this, the impacts of the life cycle stages Material production, Manufacturing, Distribution and EoL are divided by the number of uses of the reusable meal container because these impacts only take place once. For instance, even if the reusable container is only used once, the same impacts for these stages are applicable as to when it would be used 43 times. The impacts from the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages for one use cycle are multiplied by the number of uses. For the single-use meal container, the impacts of the complete life cycle are multiplied by the number of use cycles.


Figure 22: Overview of the impacts per use cycle for the impact category Global warming for all six meal boxes. The points where the lines from the reusable boxes intersect with the lines from the single-use boxes are the environmental break-even points. The lines from the single-use AL and PA boxes overlap because their values are almost equal.

Figure 22 provides an example illustration of the environmental break-even point analysis for the impact category GW. The point where the line from a reusable box intersects with the line from a single-use box represent the break-even point. It can for instance be observed from the figure that the break-even
points for this impact category are 4,5 and 8 for the reusable PP, SS and GL boxes respectively when compared with the single-use PP box. Although the break-even point of the reusable SS box is just after 4 uses, this implies that it requires at least 5 uses to result in lower environmental impacts than the single-use PP box. The figure also provides an overview of how much additional environmental impact can be prevented for each use cycle after the break-even points when a single-use box would be replaced by one of the three reusable boxes.

As explained in section 3.3, another important aspect to consider for reusable meal container systems is the return rate. A certain return rate is required to reach the environmental break-even points in practice. Unfortunately, the majority of organisations that were consulted on this topic indicated that they either did not have return rate data available, because they do not track their reusable meal containers, or that they could not disclose this type of data due to confidentiality issues. Nevertheless, it posed an interesting aspect to include in this research and therefore scenario analysis for different return rates was taken into account. Table 22 provides an overview of the maximum number of average uses of a container in practice associated with certain return rate scenarios.

Table 22: Overview of the maximum number of average uses for a reusable meal container associated with certain return rates.

| Return rate (\%) | Max average uses $(\mathrm{N})$ |
| :---: | :---: |
| $1-49$ | 1 |
| $50-66$ | 2 |
| $67-74$ | 3 |
| $75-79$ | 4 |
| $80-83$ | 5 |
| $84-85$ | 6 |
| $86-87$ | 7 |
| 88 | 8 |
| 89 | 9 |
| 90 | 10 |
| 91 | 11 |
| 92 | 12 |
| 93 | 14 |
| 94 | 16 |
| 95 | 20 |
| 96 | 25 |
| 97 | 33 |
| 98 | 50 |
| 99 | 100 |
| 100 | (technical lifetime) |

Table 23: Overview of the environmental break-even points and the associated minimum required return rates (between parentheses) for the complete life cycles of all meal container systems assessed in section 4.5.3.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Data type | BEP \| (RR) | BEP \| (RR) | BEP \| (RR) | BEP \| (RR) | BEP \| (RR) | BEP \| (RR) | BEP \| (RR) |
| Reusable PP box |  |  |  |  |  |  |  |
| Compared to the single-use PP box | 4 \| (75\%) | 4 \| (75\%) | 12 \| (92\%) | 5 \| (80\%) | 5 \| (80\%) | 6 \| (84\%) | 6 \| (84\%) |
| Compared to the single-use AL box | 13 \| (93\%) | 9 \| (89\%) | 14 \| (93\%) | 6 \| (84\%) | 6 \| (84\%) | 9 \| (89\%) | 9 \| (89\%) |
| Compared to the single-use PA box | 11 \| (91\%) | 9 \| (89\%) | 18 \| (95\%) | 7 \| (86\%) | $6 \mid$ (84\%) | 11 \| (91\%) | 8 \| (88\%) |
| Reusable SS box |  |  |  |  |  |  |  |
| Compared to the single-use PP box | 3 \| (67\%) | 5 \| (80\%) | 15 \| (94\%) | 9 \| (89\%) | 8 \| (88\%) | 11 \| (91\%) | 6 \| (84\%) |
| Compared to the single-use AL box | 10 \| (90\%) | 10 \| (90\%) | 18 \| (95\%) | 10 \| (90\%) | 11 \| (91\%) | $16 \mid$ (94\%) | 9 \| (89\%) |
| Compared to the single-use PA box | 8 \| (88\%) | 10 \| (90\%) | 22 \| (96\%) | 14 \| (93\%) | 10 \| (90\%) | 20 \| (95\%) | 8 \| (88\%) |
| Reusable GL box |  |  |  |  |  |  |  |
| Compared to the single-use PP box | 6 \| (84\%) | 8 \| (88\%) | 29 \| (97\%) | 10 \| (90\%) | 12 \| (92\%) | 9 \| (89\%) | 7 \| (86\%) |
| Compared to the single-use AL box | 19 \| (95\%) | 15 \| (94\%) | 36 \| (98\%) | 12 \| (92\%) | 16 \| (94\%) | 14 \| (93\%) | 11 \| $91 \%$ ) |
| Compared to the single-use PA box | 15 \| (94\%) | 16 \| (94\%) | 45 \| (98\%) | 16 \| (94\%) | 15 \| $94 \%$ ) | 17 \| (95\%) | 9 \| $89 \%$ ) |
| Legend impact categories and data type: CED: Cumulative energy demand, OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification, EP: Eutrophication, WU: Water use, BEP: Break-even point, RR: Return rate |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

The environmental break-even points for all impact categories were calculated for all reusable and single-use boxes assessed in section 4.5 .3 and are presented in Table 23. The minimum required return rate percentages for the break-even points to be reached in practice are indicated between parentheses in the table behind the break-even point values. From the table, it can be observed that the break-even points can differ significantly between impact categories. The break-even points are generally higher for the single-use AL and PA boxes than for the single-use PP box because lower environmental impacts are associated with these systems, as encountered in section 4.5.2. Additionally, differences between the three reusable boxes can be observed, where the highest number of uses to reach the break-even points is required for the reusable GL box. This could be expected based on the finding in section 4.5.1, namely that the reusable GL box results in the highest environmental impacts of the three reusable boxes for all impact categories. However, it is interesting to point out that for the majority of the impact categories, the environmental break-even points of the reusable PP box are reached after fewer use cycles than those of the reusable SS box. This is because the calculations for the break-even points are not based on the FU taken as the reference point for the assessments in section 4.5 .

The lowest break-even point is for the impact category CED, when the resulting environmental impacts from the reusable SS box are compared with those from the single-use PP box. The findings indicate that for this impact category the reusable SS box is already environmentally preferred over the singleuse PP box after 3 uses. In order to reach this in practice, the return rate needs to be at least $67 \%$. However, when comparing the same two boxes for the impact category OLD, it can be observed that the reusable SS box is environmentally preferred over the single-use PP box after 15 uses. For this, a return rate of at least $94 \%$ is required. Thus, in order for the reusable SS box to be environmentally preferred over the single-use PP box for all impact categories assessed in this research, the minimum required return rate is $94 \%$. This clearly illustrates how the return rate is an important aspect of reusable meal container systems. Although the reusable SS box can be used on average 200 times theoretically, with a return rate lower than $94 \%$ it will not be used enough times in practice to perform better regarding all environmental impact categories than the single-use PP box.

With the most realistic configurations for reusable meal container systems, all environmental breakeven points when comparing the reusable with the single-use boxes are reached within the technical lifetimes. Except for the impact category OLD when comparing the reusable GL box, all other breakeven points are reached after 3-22 uses. The findings indicate that the most optimal situation is when the single-use PP box is replaced by the reusable PP box. After 6 uses, which in practice is reached with a minimum return rate of $84 \%$, the reusable PP box is environmentally preferred over the single-use box PP for six out of the seven impact categories. After 6 more uses ( 12 in total), for which a return rate of $92 \%$ is required, it also performs better for the impact category OLD.

Table 24: Overview of the environmental break-even points and the associated minimum required return rates (between parentheses) for all meal container systems considered in section 4.5.4, after applying sensitivity $1 . X$ indicates that the break-even point will not be reached (within the technical lifetime).

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :--- | :---: | :--- | :--- | :--- | :--- | :--- | :---: |
| Data type | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ |
| Reusable PP box, sensitivity 1 |  |  |  |  |  |  |  |
| Compared to the single-use PP box | $6 \mid(84 \%)$ | $6 \mid(84 \%)$ | X | $8 \mid(88 \%)$ | $6 \mid(84 \%)$ | X | $16 \mid(94 \%)$ |
| Compared to the single-use AL box | X | $29 \mid(97 \%)$ | X | $12 \mid(92 \%)$ | $10 \mid(90 \%)$ | X | X |
| Compared to the single-use PA box | $31 \mid(97 \%)$ | $30 \mid(97 \%)$ | X | $27 \mid(97 \%)$ | $9 \mid(89 \%)$ | X | X |
| Reusable SS box, sensitivity 1 |  |  |  |  |  |  |  |
| Compared to the single-use PP box | $4 \mid(75 \%)$ | $7 \mid(86 \%)$ | X | $16 \mid(94 \%)$ | $10 \mid(90 \%)$ | X | $16 \mid(94 \%)$ |
| Compared to the single-use AL box | $55 \mid(99 \%)$ | $32 \mid(97 \%)$ | X | $23 \mid(96 \%)$ | $16 \mid(94 \%)$ | X | X |
| Compared to the single-use PA box | $22 \mid(96 \%)$ | $33 \mid(97 \%)$ | X | $52 \mid(99 \%)$ | $14 \mid(93 \%)$ | X | $66 \mid(99 \%)$ |
| Reusable GL box, sensitivity 1 |  |  |  |  |  |  |  |
| Compared to the single-use PP box | $8 \mid(88 \%)$ | $11 \mid(91 \%)$ | X | $18 \mid(95 \%)$ | $16 \mid(94 \%)$ | X | $19 \mid(95 \%)$ |
| Compared to the single-use AL box | X | $50 \mid(98 \%)$ | X | $26 \mid(97 \%)$ | $25 \mid(96 \%)$ | X | X |
| Compared to the single-use PA box | $43 \mid(98 \%)$ | X | X | X | $22 \mid(96 \%)$ | X | X |

Legend impact categories and data type: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use, BEP: Break-even point, RR: Return rate
Table 24 provides an overview of the environmental break-even points and the associated minimum required return rates for the three reusable boxes compared with the three single-use boxes after the first sensitivity analysis was applied. The first thing that stands out is that the break-even points will not be reached under any circumstances for the impact categories OLD and EP. This is because the impacts per use cycle from handwashing and professional dishwashing combined are larger than those from the complete life cycles of the single-use boxes. It can also be observed that the break-even points are all higher when compared with those indicated in Table 23. Interestingly, the importance of what type of single-use box is replaced by what type of reusable box now becomes more clear. The table illustrates that the break-even points for certain impact categories will not be reached when for instance the singleuse PA box is replaced, whilst they would be reached when the single-use PP box is replaced. Especially for the impact category WU these differences are noticeable. The reason for this is that there is significantly more water use associated with the life cycle of the single-use PP box than with those of the single-use AL and PA boxes.

Table 25: Overview of the environmental break-even points and the associated minimum required return rates (between parentheses) for all meal container systems considered in section 4.5.4, after applying sensitivity $2 . X$ indicates that the break-even point will not be reached (within the technical lifetime).

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Data type | BEP $\mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ |
| Reusable PP box, sensitivity 2 <br> Compared to the single-use PP box | $7 \mid(86 \%)$ | $11 \mid(91 \%)$ | X | X | $9 \mid(89 \%)$ | $12 \mid(92 \%)$ | $7 \mid(86 \%)$ |
| Reusable SS box, sensitivity 2 <br> Compared to the single-use PP box | $5 \mid(80 \%)$ | $12 \mid(92 \%)$ | X | X | $15 \mid(94 \%)$ | $22 \mid(96 \%)$ | $7 \mid(86 \%)$ |
| Reusable GL box, sensitivity 2 <br> Compared to the single-use PP box | $9 \mid(89 \%)$ | $19 \mid(95 \%)$ | X | X | $24 \mid(96 \%)$ | $19 \mid(95 \%)$ | $8 \mid(88 \%)$ |

Legend impact categories and data type: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use, BEP: Break-even point, RR: Return rate

Table 26: Overview of the environmental break-even points and the associated minimum required return rates (between parentheses) for all meal container systems considered in section 4.5.4, after applying sensitivity 3.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Data type | BEP $\mid(\mathrm{RR})$ | BEP $\mid(\mathrm{RR})$ | BEP $\mid(\mathrm{RR})$ | BEP $\mid(\mathrm{RR})$ | BEP $\mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ | $\mathrm{BEP} \mid(\mathrm{RR})$ |
| Reusable PP box, sensitivity 3 <br> Compared to the single-use PP box | $5 \mid(80 \%)$ | $5 \mid(80 \%)$ | $10 \mid(90 \%)$ | $5 \mid(80 \%)$ | $5 \mid(80 \%)$ | $8 \mid(88 \%)$ | $6 \mid(84 \%)$ |
| Reusable SS box, sensitivity 3 <br> Compared to the single-use PP box | $3 \mid(67 \%)$ | $5 \mid(80 \%)$ | $13 \mid(93 \%)$ | $9 \mid(89 \%)$ | $8 \mid(88 \%)$ | $14 \mid(93 \%)$ | $6 \mid(84 \%)$ |
| Reusable GL box, sensitivity 3 <br> Compared to the single-use PP box | $6 \mid(84 \%)$ | $8 \mid(88 \%)$ | $26 \mid(97 \%)$ | $11 \mid(91 \%)$ | $12 \mid(92 \%)$ | $12 \mid(92 \%)$ | $7 \mid(86 \%)$ |

Legend impact categories and data type: CED: Cumulative energy demand, GW: Global warming, OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use, BEP: Break-even point, RR: Return rate
Table 25 and Table 26 contain the environmental break-even points and the associated minimum required return rates for the three reusable boxes compared with the single-use PP box after the second and third sensitivity analyses were applied. Only the single-use PP box is taken into account because no such differences as in Table 24 were encountered. It is not the case that, for a specific impact category, the break-even points are either reached after a certain number of uses or are not reached (within the technical lifetime), depending on with which single-use box the reusable is compared. The break-even points when compared with the single-use AL and PA boxes are higher, but this was already indicated in Table 23. From Table 25, it can be observed that the break-even points for the impact categories OLD and PO will never be reached. This is because the impacts from a retrieval round with a scooter per use cycle are larger than those from the complete life cycles of the single-use boxes. Table 26 shows that almost all break-even points are only marginally higher when compared with those indicated in Table 23. Remarkably, for the impact category OLD, they are lower because conventional dishwashing results in lower impacts for this category than professional dishwashing. The break-even point tables after applying the sensitivity analyse again indicate the importance of which configurations are applied to reusable meal container systems for the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages.

## 5. Discussion

In this chapter, the most important discussion points encountered in this research are described. The obtained results are discussed in line with the research objective. The main limitations encountered during the research are described first.

### 5.1 Limitations

Despite that LCA is nowadays a widely accepted method, concurrently, there is a variety of limitations associated with it. In general, LCA makes use of simplified models, to which assumptions and scenarios are applied, in order to assess the resulting impacts from product systems used in the complex real world (Curran, 2014). However, in this research, the modelling was performed in such a way that the product systems are described as well as possible. In order to reduce the probability of similar LCA studies leading to varying results, all used data and methods in this research were transparently documented.

Another limitation of LCA is that it often mainly focuses on the environmental impacts, overlooking the economic and social impacts. In this research, these two aspects were also not assessed. The obtained results therefore cannot indicate whether incorporating reusable meal container systems would also be economically viable for restaurant owners. Moreover, recently published research by Muncke et al. (2020) concluded that often the chemical safety of food contact materials is not adequately taken into account with the urgent demand to reduce packaging waste. Additional research on these aspects of meal containers of different material types is required.

The circularity of reusable meal containers in comparison with single-use alternatives could not be properly assessed in this research, because there is not yet a circularity indicator included in SimaPro. There is an ongoing scientific discussion on circularity indices. Research by Corona et al. (2019) assessed multiple circularity metrics, among which seven indices. The authors concluded that there is currently no metric that takes into account all validity requirements of the CE. Those requirements address all three dimensions of sustainable development, namely environment, economy and society. LCA poses a promising framework for assessing circularity, however, in this research only the environmental dimension was studied. The findings of this research indicated that by adopting a systems thinking approach, reusable meal container systems can result in lower environmental impacts for all impact categories than single-use systems. Because of the focus on reusing, which results in significantly less material required for the production, it is expected that reusable meal container systems are more circular than single-use ones regarding the environment dimension. If future studies would aim to assess the circularity of reusable meal container systems, it is important that the economic and social facets of sustainability are also assessed.

In this research, no weighting was applied to the obtained environmental impacts for different impact categories. Therefore, the obtained results could sometimes not indicate whether a reusable meal container systems was evidently environmentally preferred over a single-use system, only when a reusable system resulted in lower impacts for all impact categories. However, the obtained results after applying the first two sensitivity analyses indicated that often a reusable system results in lower impacts for the majority of impact categories, but not for OLD, PO and WU. It also depends on which of the impact categories are deemed most important whether a certain system can be considered environmentally preferred over another.

### 5.2 Model robustness

The models that were established during this research are expected to be representative for reusable and single-use meal container systems, and the potential configurations through which these systems can be implemented, in Belgium and the Netherlands. Because of the iterative nature of this comparative LCA,
the models were checked for completeness and consistency repeatedly to reach a high level of robustness. Composing the initial two models with readily available data enabled contribution and dominance analyses at an early stage. This identified which of the life cycle stages contributed significantly to the total impacts, which limited the range for additional data collection. Assessing the impacts of different system configurations for the dominant life cycle stages individually resulted in a clear overview of the worst-case options. This provided a solid basis for the sensitivity analyses to check the sensitivity of the obtained results. During the research process, the models were rerun repeatedly and the findings were regularly discussed with the supervisors. Any aspects that were still missing were included in the models. The reasons for any inconsistencies encountered were tracked down and the models were improved accordingly. Therefore, regarding the criteria from Baitz et al. (2013), it is expected that the obtained results are reliable. The results were presented in percentual contributions to obtain a clear overview of how the different systems and configurations compare with each other, to ensure the applicability in existing practices in business. Additionally, the results were presented in absolute values to also provide quantitative information.

To establish uncertainty ranges, it was decided to collect additional data for the dominant life cycle stages of the reusable meal container systems only. The uncertainty ranges were established by applying multiple data sources of alternative input data to the component included in an option that was expected to be the major contributor to the total impact of that option. These were mainly the energy used during the customer and professional cleaning options and the types of vehicles used for the scenarios of recollecting the containers. Although uncertainty is already taken into account in most ecoinvent datasets (ecoinvent, 2019), establishing uncertainty ranges also for the other less influential life cycle stages would improve the robustness and reliability of the results even further. However, it is not expected that the obtained results will alter significantly because of this.

In this research, wastewater treatment could not be modelled according to the CFF, because there are no default values for the CFF parameters available for this. No other proper allocation method for attributing the burdens and credits from this process partially to the current and subsequent life cycles was encountered. Further research could aim to find an approach for this, in order to remain consistent in the allocation procedure for all system components included in the modelling.

A minor modelling mistake was encountered in a late stage of the research, namely that the impacts from the transportation to recycling facilities were not included. It was checked whether this could have influenced the obtained results. The additional impacts in the EoL stage for all material types were insignificant. Therefore, and because of time constraints, it was decided not to adjust the Results chapter accordingly. However, the additional impacts were added to the Excel tool in order for it to be as accurate as possible. For this, an average distance of 50 km to recycling facilities for all material types was included (Bijleveld et al., 2021; Gallego-Schmid et al., 2019). Users of ecoinvent should be aware of what is included in each dataset and what is not, to avoid these types of modelling mistakes.

### 5.3 Data uncertainty

The data used to model the life cycles of meal container systems were based on the most suitable datasets that were encountered during this research regarding temporal, geographical and technological representativeness. However, for several aspects data older than five years were used and assumptions had to be made. European and Global data were furthermore used where the availability of more specific regional data was lacking. For the Material production and Manufacturing stages, several assumptions were made for the reusable SS box and the single-use PA box. Consequently, the obtained resulting impacts from these two boxes might differ marginally, but the results are expected to be the same. Most reusable meal containers that are currently available are made from plastics. Comparing the
environmental impacts, durability and recyclability of meal containers from different types of plastic would pose an interesting topic for additional research.

The impacts resulting from the Distribution stage were based on the weights and distances for freight transportation. Both form the input data to calculate the tkm, the unit required for calculating the environmental impacts of transport. In practice, the volume of a container might limit the carrying capacity of a transportation vehicle. Especially for reusable containers, this is an aspect to take into account because, depending on their form, these may not be as efficiently stackable as single-use containers. If a transportation vehicle because of this can theoretically carry fewer containers during the distribution, this would result in higher impacts from this life cycle stage. However, it is not expected that this would significantly influence the results, because the Distribution stage generally contributes least to the total impacts of the life cycles of meal container systems. Furthermore, the manufacturing and EoL of distribution packaging were not taken into account in this research, because it was expected that the resulting impacts would be negligible in comparison to the total impacts.

For the energy use of the customer and professional cleaning options, European datasets were included in the models in order for the resulting environmental impacts to be appliable to both Belgium and the Netherlands. However, the resulting impacts from these processes could be different when modelling this for specific European countries because the electricity mix differs per country. In the tool, a distinction was made between Belgian- and Dutch-specific electricity mixes. The use of paper towels included for handwashing is an expected worst-case scenario because it could also be possible that customers dry the containers with a dishcloth or on a drying rack, which might result in lower impacts. Nevertheless, this scenario was included to obtain a clear overview of how this configuration for reusable meal container systems can influence the results when compared with single-use systems. For the professional cleaning options, the impacts from the dishwashers were not taken into account, because no suitable datasets were encountered to model this for professional and industrial dishwashers.

The retrieval and redistribution scenarios were modelled mainly based on assumptions because actual data for this were not yet available. Further research is required to collect such actual data for the characteristics of this life cycle stage in practice, ideally during pilot trials with reusable meal containers. ecoinvent datasets were adjusted to obtain datasets for a scooter and a van representative for those expected to be used in reusable meal container systems. Even though careful considerations were made during this process, the accuracy of the resulting impacts from these datasets cannot be guaranteed.

The environmental impacts resulting from the EoL stage of all meal containers were assessed based mainly on Dutch data. More accurate data for the Netherlands than for Belgium were encountered during this research for material recycling percentages and electricity and heat recovered during incineration with energy recovery. Because of this, the obtained results from this life cycle stage are less accurate for the Belgian region. Nevertheless, it can be expected that this would not have led to significant differences in impacts, because the differences in the majority of recycling percentages for instance are small. Thus, the results of the complete life cycles are expected to also be applicable to Belgium. In the tool, both Belgian- and Dutch-specific data for the EoL stage were included. Furthermore, because LCA is often criticised for not including litter, this research aimed to include this aspect by taking into account material leakage (i.e. system delineation). Leakage of material types other than plastics was also assumed to be $2.5 \%$ on average because specific data for this aspect for other materials were not encountered. The same percentage of material leakage was included for both reusable and single-use meal containers, which is a worst-case scenario for the reusables. In practice, it can be expected that the material leakage from reusable containers is lower than from single-use ones because of the focus on recollecting. This approach was not ideal and it was thus decided not to include littering in the tool, because there is no consensus yet on how to properly address litter in LCA. Marine litter indicators are
currently being developed (Civancik-Uslu et al., 2019; Stefanini et al., 2021). Therefore, future research on meal containers could look into the potential of including littering impact through such an indicator.

### 5.4 Comparing results with previous research

The obtained results for the reusable meal containers considered in this research correspond with previous research by Gallego-Schmid et al. (2018). The environmental impacts of glass containers are higher for all impact categories than those from plastic and the use stage is the largest contributor to the impacts from the complete life cycles. Since this research was the first to include the assessment of a steel container, the obtained results could not be compared with previous research. The obtained results for the single-use meal containers considered in this research correspond largely with previous research by Gallego-Schmid et al. (2019). The environmental impacts of plastic containers are higher for the majority of impact categories than those from aluminium. However, contradicting results were encountered for the impact category OLD. This can be partly explained by the fact that in this research a higher recycling percentage was included for aluminium ( $95 \%$ based on a Dutch waste treatment scenario as opposed to $54 \%$ based on EU averages). For take-away food packaging materials in general, the obtained results correspond largely with previous studies (UNEP, 2020). Paper packaging performs environmentally better than plastic packaging and often also than aluminium packaging.

When taking the most realistic configurations into account for reusable meal container systems, the obtained results in this research correspond with those encountered in previous studies on take-away food packaging (Baumann et al., 2018; Harnoto, 2013; UNEP, 2020). In general, reusable alternatives are environmentally preferred over single-use packaging, provided that they are used at least a certain amount of times at which the environmental break-even points are reached. The importance of what cleaning methods are applied to the reusable meal containers and how they are recollected are often also highlighted. Overall, the results obtained during this research can thus be considered reliable. Only for the impacts resulting from the different retrieval and redistribution scenarios, no clear comparison material was encountered. Future research is required to reach robust results for this life cycle stage.

Remarkably, the resulting environmental impacts from the amounts of water used during the life cycles of the reusable meal container systems obtained in this research differ partly from what was established in previous research on reusable food packaging (Baumann et al., 2018; Harnoto, 2013). The reason for this could be that in those studies other impact assessment methods were used to determine the water use or that wastewater treatment was not considered. Both were not clearly indicated in those studies. Because this is an under-represented aspect of research on meal containers specifically, the results from previous studies on reusable tableware were also considered for this comparison (UNEP, 2021). The majority of those studies concluded that the water use of reusable items is higher when compared with single-use items in almost all scenarios as a result of washing. However, the findings from this research pointed out that, with the majority of the system configurations, reusable meal containers are environmentally preferred over single-use ones regarding the impact category WU . This can mainly be attributed to the high amounts of water used during the Material production stage of the single-use boxes. In order to avoid misunderstandings in future debates on this topic, it is important that this aspect is taken into account in further research on reusable meal containers.

### 5.5 Return rate under-represented in previous research

A key aspect dominantly influencing the life cycle results of reusable meal container systems is the return rate. The return rate influences how many times a reusable container can be used in practice. This aspect has been under-represented in previous research on reusable take-away food packaging. Only the research performed by Baumann et al. (2018) incorporated the return rates, but the authors indicated that this data first has to be collected during pilot trials with reusable containers. During this research, it was
also encountered that this type of data is often either not available to organisations working with reusable meal containers or that it cannot be disclosed due to confidentiality issues. Therefore, this research included an opposite approach in section 4.6 by identifying the associated minimum return rates required for the environmental break-even points presented in the tables to be reached in practice. It is important to note that part of the containers that are not returned could also be used by the customers for other purposes which might result in lower environmental impacts (e.g. food waste reduction). The environmental benefits that would potentially result from this were not considered in this research.

Previous research on return systems for reusable packaging items was consulted in order to provide an overview of the most important aspects influencing return rates. Of major importance to establish high return rates is the introduction of a Deposit Refund System (DRS). An average return rate of $40 \%$ in Europe can increase to $80-90 \%$ as a result of the introduction of such a system (Schneider et al., 2019). The success often depends on the deposit fee that is introduced to stimulate customers to return their reusable items. Research by Bergsma et al. (2017) concluded that a return rate of $90 \%$ could be realised by introducing a suitable deposit fee for small PET bottles and aluminium cans in the Netherlands. Thus, the correct amount of deposit fee for reusable meal containers needs to be established for the most optimal effect of the system. Moreover, establishing collaboration across multiple participating restaurants (i.e. pooling) could contribute to improving the return rates by for instance creating more sufficient systems to recollect the meal containers. Standardisation of reusable meal containers used in delivery and take-away systems can also contribute to establishing efficient pooling systems (Coelho et al., 2020). Research by Zimmermann \& Bliklen (2020) indicated that this poses an interesting topic for further research on reusable packaging items. To summarise, the optimalisation of the return rate in general is an important aspect to focus on in future research on reusable meal container systems.

## 6. Conclusion and recommendations

This research aimed to identify how food delivery and take-away systems with reusable and single-use meal containers with different configurations compare with each other from an environmental life cycle perspective in Belgium and the Netherlands. LCAs were performed to determine the environmental impacts resulting from the complete life cycles of these product systems. Multiple configurations are possible for the life cycle stages Customer cleaning, Retrieval and redistribution, and Professional cleaning of reusable meal container systems. These stages also contribute most to the total impacts of those product systems. The resulting impacts from the options that are possible from each of these life cycle stages were assessed and compared individually, before comparing the whole life cycles.

It can be concluded that no cleaning or cold water rinsing is the environmentally preferred customer cleaning method. Handwashing results in the highest environmental impacts. Although the reusable containers do not necessarily have to be cleaned by the customer, it can be expected that customers will feel the urge to apply some type of cleaning because of the hygiene issues associated with food residue. It is therefore recommended to clearly communicate to customers to apply cold water rinsing. This will ensure that they do not clean it by a method resulting in higher environmental impacts and prevent any potential confusion regarding whether they are expected to thoroughly clean it themselves.

For recollecting the containers after use, making use of at-home/at-restaurant exchanges is the environmentally preferred option because no additional transportation distances and associated impacts are required for this. If this scenario is not feasible, making use of scenarios in which electric transportation vehicles are used and the least amount of km has to be travelled on average for recollecting a container are preferred. It is recommended to then focus on creating efficient drop-off point systems because the results indicated that these scenarios are often preferred over retrieval rounds.

It can be concluded that industrial dishwashing is the environmentally preferred professional cleaning method for six out of the seven impact categories. Conventional dishwashing results in the largest impacts, except for the category OLD. However, if for industrial dishwashing large additional transportation distances are required or organisations do not want to outsource this process, professional dishwashing is the most suitable option. The electricity use is the largest contributing process to the total resulting impacts from this option, followed by the use of detergent. It is thus recommended for organisations working with reusable meal containers to search for professional cleaning options with high energy efficiencies and environmentally friendly detergent alternatives.

From the results it can be concluded that, with the most realistic configurations included, reusable meal container systems are environmentally preferred over single-use systems for all seven impact categories assessed in this research. However, when applying different configurations to the systems, this is not always the case. From the sensitivity analyses, it can be concluded that especially the customer cleaning method and the method for retrieving and redistributing the containers are decisive. The type of professional cleaning method applied is also of importance. However, the resulting impacts did not change as drastically as for the other two dominant life cycle stages when including the worst-case option. Stainless steel proved to be the preferred material type for reusable meal containers from an environmental perspective because of its high durability and recyclability. Recycling Netwerk Benelux is advised to continue encouraging restaurant owners and other users of meal containers to incorporate the switch from single-use to reusable, with emphasis on the importance of establishing environmentally favourable system configurations. The Excel tool developed as part of this research project can be a contributing factor to this, by providing users with insights into how they can optimally arrange their reusable systems from an environmental perspective. Organisations that want to work with reusable meal containers are advised to look into the potential of using stainless steel containers or containers
from other material types with a high durability resulting in a long technical lifetime. The recyclability of those materials is also an important factor to consider, especially when part of the objective is to reach a more circular system.

The results showed that all environmental break-even points are reached within the technical lifetimes when the most realistic configurations for reusable meal container systems are taken into account. Nevertheless, the results also indicated the importance of the return rates, which can limit the number of times a reusable meal container can be used in practice. A relatively high return rate (at least $92 \%$ ) is required to reach the environmental break-even points for all impact categories. Recycling Netwerk Benelux is advised to highlight the importance of the return rate of reusable meal container systems in their communication towards organisations within this industry sector. This aspect appears to be overlooked often both in research on this topic and in practice. Additionally, it is important to focus on bringing these types of organisations in contact with each other to encourage them to work together and share experiences. It is recommended to organisations working with reusable meal containers to try to reach as high as possible return rates, for instance by establishing the most optimal deposit fee.

To summarise, reusable meal container systems in Belgium and the Netherlands are environmentally preferred over single-use ones from a life cycle perspective, provided that correct (i.e. environmentally preferable) configurations are included in those systems. It is important to note that in this research generic LCAs were performed, not full-blown (detailed) LCAs. Thus, the results obtained from using the Excel tool only provide a good first indication of the impacts. The quality of those results depends on the quality of the input data filled in by the users. Communication between actors within this industry sector on topics as cleaning methods, methods for recollecting the containers and return rates appears to be key in realising that reusable systems are implemented in such a manner that they result in lower environmental impacts than single-use ones.

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## Appendix A: ecoinvent datasets

Tables A.1, A. 2 and A. 3 provide an overview of the most suitable ecoinvent datasets that were encountered and used during this research for each of the system components. Only for recycling steel, an APOS dataset was used because no suitable Cut-off dataset was encountered for this process.

Table A.1: ecoinvent datasets used for modelling the Material production and Manufacturing stages during this research.

| System components | Most suitable ecoinvent datasets |
| :---: | :---: |
| Material production |  |
| Polypropylene | Polypropylene, granulate \{GLO\}\| market for | Cut-off, U |
| Silicone | Silicone product \{RER\}\| market for silicone product | Cut-off, U |
| Chromium steel | Steel, chromium steel $18 / 8$ \{GLO\}\| market for | Cut-off, U |
| Chromium steel recycled content | Steel, chromium steel $18 / 8$ \{GLO\}\| market for | Cut-off, U |
| Sorting steel (for recycled content) | Iron scrap, sorted, pressed \{RER\}\| sorting and pressing of iron scrap | Cut-off, U |
| Recycling steel (for recycled content) | Iron scrap, unsorted $\{$ RoW\}\| steel production, electric, low-alloyed | APOS, U |
| White glass | Packaging glass, white $\{$ GLO $\} \mid$ market for \| Cut-off, U |
| White glass recycled content | Packaging glass, white $\{$ GLO $\} \mid$ market for \| Cut-off, U |
| Recycling glass (for recycled content) | Glass cullet, sorted \{GLO\}\| market for | Cut-off, U |
| Aluminium | Aluminium, primary, liquid \{GLO\}\| market for | Cut-off, U |
| Aluminium (recycled content) | Aluminium, primary, liquid \{GLO\}\| market for | Cut-off, U |
| Recycling aluminium (for recycled content) | Aluminium, cast alloy $\{\mathrm{RER}\} \mid$ treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner \| Cut-off, U |
| Paper | Kraft paper, unbleached \{GLO\}\| market for | Cut-off, U |
| Paper (recycled content) | Kraft paper, unbleached \{GLO\}\| market for | Cut-off, U |
| Recycling paper (for recycled content) | Graphic paper, $100 \%$ recycled \{GLO\}\| market for | Cut-off, U |
| Polyethylene | Polyethylene, high density, granulate \{GLO\}\| market for | Cut-off, U |
|  |  |
| Manufacturing |  |
| Plastic extrusion and thermoforming | Extrusion of plastic sheets and thermoforming, inline \{GLO\}\| market for | Cut-off, U |
| Steel sheet rolling | Sheet rolling, chromium steel \{GLO\}\| market for | Cut-off, U |
| Steel deep drawing | Deep drawing, steel, 3500 kN press, automode $\{$ GLO $\} \mid$ market for \| Cut-off, U |
| Glass melting (electricity) | Electricity, medium voltage $\{\mathrm{CN}\} \mid$ market group for $\mid$ Cut-off, U |
| Glass melting (heat) | Heat, district or industrial, natural gas \{GLO\}\| market group for | Cut-off, U |
| Glass tempering | Tempering, flat glass $\{$ GLO $\} \mid$ market for \| Cut-off, U |
| Aluminium sheet rolling | Sheet rolling, aluminium \{GLO\}\| market for | Cut-off, U |
| Aluminium impact extrusion | Impact extrusion of aluminium, 1 stroke $\{$ GLO $\} \mid$ market for $\mid$ Cut-off, U |
| Paper lid production (electricity) | Electricity, medium voltage $\{\mathrm{CN}\} \mid$ market group for $\mid$ Cut-off, U |
| Paper lid production (heat) | Heat, district or industrial, natural gas \{GLO\}\| market group for | Cut-off, U |
| Paper box production (electricity) | Electricity, medium voltage $\{\mathrm{CN}\} \mid$ market group for \| Cut-off, U |

Table A.2: ecoinvent datasets used for modelling the Distribution, Customer cleaning, Retrieval and redistribution, and Professional cleaning stages during this research.

| System components | Most suitable ecoinvent datasets |
| :---: | :---: |
| Distribution |  |
| Packaging - core board | Core board \{GLO\}\| market for | Cut-off, U |
| Packaging - polyethylene | Polyethylene, high density, granulate \{GLO\}\| market for | Cut-off, U |
| Transportation - lorry 16-32 ton (RoW) | Transport, freight, lorry 16-32 metric ton, euro6 \{RoW\}\| market for transport, freight, lorry 16-32 metric ton, EURO6|Cut-off, U |
| Transportation - container ship | Transport, freight, sea, container ship \{GLO\}\| market for transport, freight, sea, container ship | Cut-off, U |
| Transportation - lorry 16-32 ton (RER) | Transport, freight, lorry 16-32 metric ton, euro6 \{RER\}\| market for transport, freight, lorry 16-32 metric ton, EURO6| Cut-off, U |
|  |  |
| Customer cleaning |  |
| Water | Tap water \{Europe without Switzerland\}\| market for | Cut-off, U |
| Energy (heat) | Heat, central or small-scale, natural gas \{Europe without Switzerland\}\| market for heat, central or small-scale, natural gas | Cut-off, U |
| Soap | Soap \{GLO\}\| market for | Cut-off, U |
| Paper towels | Tissue paper $\{$ GLO $\}$ \| market for $\mid$ Cut-off, U |
| Recycling paper (for recycled content) | Graphic paper, $100 \%$ recycled \{GLO\}\| market for |Cut-off, U |
| Incinerating paper | Waste graphical paper $\{\mathrm{NL}\} \mid$ market for waste graphical paper \| Cut-off, U |
| Electricity (retrieved from paper) | Electricity, medium voltage \{NL\}\| market for | Cut-off, U |
| Heat (retrieved from paper) | Heat, district or industrial, other than natural gas \{Europe without Switzerland\}\| market for heat, district or industrial, other than natural gas |Cut-off, U ( |
| Disposal paper | Waste graphical paper $\{\mathrm{NL}\} \mid$ market for waste graphical paper \| Cut-off, U |
| Wastewater treatment | Wastewater, average \{Europe without Switzerland\}\| treatment of wastewater, average, capacity 1E91/year |Cut-off, U |
| Energy (electricity) | Electricity, low voltage \{Europe without Switzerland\}\| market group for | Cut-off, U |
| Salt | Salt \{GLO\}\| market for salt | Cut-off, U |
| Dishwasher | Dishwasher \{GLO\}\| market for dishwasher | Cut-off, U |
|  |  |
| Retrieval and redistribution |  |
| Transportation - electric bicycle* | Transport, passenger, electric bicycle \{GLO\}\| market for | Cut-off, U Transport, passenger, electric bicycle, label-certified electricity $\{\mathrm{GLO}\} \mid$ market for \| Cut-off, U |
| Transportation - scooter* | Transport, passenger, motor scooter \{GLO\}\| market for | Cut-off, U |
| Transportation - van* | Transport, passenger car, medium size, diesel, EURO 5 \{RER $\} \mid$ transport, passenger car, medium size, diesel, EURO $5 \mid$ Cut-off, U |
|  |  |
| Professional cleaning |  |
| Water | Tap water \{Europe without Switzerland\}\| market for | Cut-off, U |
| Energy (electricity) - low voltage | Electricity, low voltage \{Europe without Switzerland\}\| market group for | Cut-off, U |
| Soap | Soap \{GLO\}\| market for | Cut-off, U |
| Salt | Salt \{GLO\}\| market for salt | Cut-off, U |
| Wastewater treatment | Wastewater, average \{Europe without Switzerland\}\| treatment of wastewater, average, capacity 1E91/year | Cut-off, U |
| Detergent ( NaOH ) | Sodium hydroxide, without water, in $50 \%$ solution state \{GLO\}\| market for | Cut-off, U |
| Energy (electricity) - medium voitage | Electricity, medium voltage \{Europe without Switzerland\}\| market group for $\mid$ Cut-off, U |
| *Datasets were adjusted in order to obtain datasets representative for the system components considered in this research |  |

Table A.3: ecoinvent datasets used for modelling the End-of-Life stage during this research.

| System components | Most suitable ecoinvent datasets |
| :---: | :---: |
| End-of-Life |  |
| Sorting polypropylene | Waste polyethylene, for recycling, sorted \{Europe without Switzerland\}\| treatment of waste polyethylene, for recycling, unsorted, sorting | Cut-off, U |
| Recycling polypropylene | Polyethylene, high density, granulate, recycled \{Europe without Switzerland\}\| market for polyethylene, high density, granulate, recycled | Cut-off, U |
| Polypropylene (retrieved from recycling) | Polypropylene, granulate \{GLO\}\| market for | Cut-off, U |
| Incinerating polypropylene (and silicone) | Waste polypropylene \{NL\}\| market for waste polypropylene | Cut-off, U |
| Electricity (retrieved from polypropylene) | Electricity, medium voltage \{NL\}\| market for | Cut-off, U |
| Heat (retrieved from polypropylene) | Heat, district or industrial, other than natural gas \{Europe without Switzerland\}\| market for heat, district or industrial, other than natural gas | Cut-off, U |
| Electricity (retrieved from silicone) | Electricity, medium voltage $\{\mathrm{NL}\} \mid$ market for \| Cut-off, U |
| Heat (retrieved from silicone) | Heat, district or industrial, other than natural gas \{Europe without Switzerland\}\| market for heat, district or industrial, other than natural gas | Cut-off, U |
| Disposal polypropylene (and silicone) | Waste polypropylene $\{\mathrm{NL}\} \mid$ market for waste polypropylene \| Cut-off, U |
| Sorting steel | Iron scrap, sorted, pressed \{RER\}\| sorting and pressing of iron scrap | Cut-off, U |
| Recycling steel | Iron scrap, unsorted \{RoW\}\| steel production, electric, low-alloyed | APOS, U |
| Chromium steel (retrieved from recycling | Steel, chromium steel 18/8 \{GLO\}\| market for | Cut-off, U |
| Disposal steel | Scrap steel \{Europe without Switzerland\}\| treatment of scrap steel, municipal incineration | Cut-off, U |
| Recycling glass | Glass cullet, sorted \{GLO\}\| market for | Cut-off, U |
| White glass (retrieved from recycling) | Packaging glass, white \{GLO\}\| market for | Cut-off, U |
| Disposal glass | Waste glass $\{\mathrm{NL}\} \mid$ market for waste glass \| Cut-off, U |
| Recycling aluminium | Aluminium, cast alloy \{RER\}\| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Cut-off, U |
| Aluminium (recovered from recycling) | Aluminium, primary, liquid \{GLO\}\| market for | Cut-off, U |
| Recycling paper | Graphic paper, 100\% recycled \{RER\}\| production | Cut-off, U |
| Paper (recovered from recycling) | Kraft paper, unbleached \{GLO\}\| market for | Cut-off, U |
| Sorting polyethylene | Waste polyethylene, for recycling, sorted \{Europe without Switzerland\}\| treatment of waste polyethylene, for recycling, unsorted, sorting | Cut-off, U |
| Recycling polyethylene | Polyethylene, high density, granulate, recycled \{Europe without Switzerland\}\| market for polyethylene, high density, granulate, recycled | Cut-off, U |
| Polyethylene (recovered from recycling) | Polyethylene, high density, granulate \{GLO\}\| market for | Cut-off, U |
| Incinerating paper | Waste graphical paper \{NL\}\| market for waste graphical paper | Cut-off, U |
| Incinerating polyethylene | Waste polyethylene $\{\mathrm{NL}\} \mid$ market for waste polyethylene \| Cut-off, U |
| Electricity (retrieved from paper) | Electricity, medium voltage \{NL\}\| market for | Cut-off, U |
| Heat (retrieved from paper) | Heat, district or industrial, other than natural gas \{Europe without Switzerland\}\| market for heat, district or industrial, other than natural gas | Cut-off, U |
| Electricity (retrieved from polyethylene) | Electricity, medium voltage $\{\mathrm{NL}\} \mid$ market for \| Cut-off, U |
| Heat (retrieved from polyethylene) | Heat, district or industrial, other than natural gas \{Europe without Switzerland\}\| market for heat, district or industrial, other than natural gas | Cut-off, U |
| Disposal aluminium | Scrap aluminium \{Europe without Switzerland\}\| treatment of scrap aluminium, municipal incineration | Cut-off, U |
| Disposal paper | Waste graphical paper \{NL\}\| market for waste graphical paper | Cut-off, U |
| Disposal polyethylene | Waste polyethylene \{NL\}\| market for waste polyethylene | Cut-off, U |

## Appendix B: Circular Footprint Formula parameters

In this research, the EoL stage of the different meal containers was modelled according to the CFF. Figure B. 1 contains a description of what each of the parameters entails.

A: allocation factor of burdens and credits between supplier and user of recycled materials.
B: allocation factor of energy recovery processes. It applies both to burdens and credits.
Qsin: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.
Qsout: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.
$\mathbf{Q}_{\mathbf{p}}$ : quality of the primary material, i.e. quality of the virgin material.
$\mathbf{R}_{\mathbf{1}}$ : it is the proportion of material in the input to the production that has been recycled from a previous system.
R2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.
R3: it is the proportion of the material in the product that is used for energy recovery at EoL.
Erecycled (Erec): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.
ErecyclingEol (ErecEoL): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.
$\mathbf{E v}_{\mathrm{v}}$ : specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
$\mathbf{E}_{\mathrm{v} \text { : }}$ specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
Eer: specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.).
EsE,heat and EsE,elec: specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.
ED: specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.
$\mathbf{X e r}_{\text {ER,heat }}$ and $\mathbf{X}_{\text {ER,elec: }}$ the efficiency of the energy recovery process for both heat and electricity.
LHV: lower heating value of the material in the product that is used for energy recovery.
Figure B.1: Overview of what each of the parameters included in the Circular Footprint Formula entails (adapted from Zampori \& Pant, 2019).

The parameters differ per different material type. Table B. 1 indicates the values for the parameters of the CFF for the different material types that were used in this research. The PEF guide indicates that it is recommended to use a value of 0 for parameter B , however, in this research it was assumed that the value for parameter B equals the value for parameter A (B. Corona, personal communication, January 26, 2021).

Table B.1: Overview of the values for the parameters of the Circular Footprint Formula used in this research.

| Parameters | Value | Parameters | Value | Parameters | Value |
| :--- | :---: | :--- | :---: | :--- | :---: |
| Polypropylene |  | Glass |  | Polyethylene |  |
| A | 0.5 | A | 0.2 | A | 0.5 |
| B | 0.5 | B | 0.2 | B | 0.5 |
| Qsin/Qp | 0.9 | Qsin/Qp | 1 | Qsin/Qp | 0.9 |
| Qsout/Qp | 0.9 | Qsout/Qp | 1 | Qsout/Qp | 0.9 |
| R1 | 0 | R1 | 0.4 | R1 | 0 |
| R2 | 0.35 | R2 | 0.71 | R2 | 0.35 |
| R3 | 0.6305 | R3 | 0 | R3 | 0.6305 |
| LHV | 40.34 |  |  | LHV | 39.93 |
|  |  | Aluminium |  |  |  |
| Silicone |  | A | 0.2 | Tissue paper |  |
| A | 0.5 | B | 0.2 | A | 0.5 |
| B | 0.5 | Qsin/Qp | 1 | B | 0.5 |
| Qsin/Qp | 0.9 | Qsout/Qp | 1 | Qsin/Qp | 0.85 |
| Qsout/Qp | 0.9 | R1 | 0.32 | Qsout/Qp | 0.85 |
| R1 | 0 | R2 | 0.95 | R1 | 0.25 |
| R2 | 0 | R3 | 0 | R2 | 0 |
| R3 | 0.97 |  |  | R3 | 0.97 |
| LHV | 10 | Paper |  | LHV | 20.7 |
|  |  | A | 0.2 |  |  |
| Steel |  | B | 0.2 | For all material types |  |
| A | 0.2 | Qsin/Qp | 0.85 | Xer,heat | 0.23 |
| B | 0.2 | Qsout/Qp | 0.85 | Xer,elec | 0.2 |
| Qsin/Qp | 1 | R1 | 0.17 |  |  |
| Qsout/Qp | 1 | R2 | 0.87 |  |  |
| R1 | 0.75 | R3 | 0.1261 |  |  |
| R2 | 0.95 | LHV | 20.7 |  |  |
| R3 | 0 |  |  |  |  |

The values for all E parameters were not specified in the above table, because multiple impact categories were assessed in this research. The values differ per impact category because each category is assessed using different units. The values for the E parameters correspond with the selected ecoinvent datasets, although these still have to be corrected according to the FU used in the research. It was therefore decided to rewrite the formula in such a way that all E parameters become separate and can be calculated by filling in the rest of the parameters and multiply this by the correct input or output amount according to the FU. For instance, for the second component of the formula, this was established as follows:

R1 * (A * Erec + (1-A) * Ev * Qsin/Qp)
$=\mathrm{R} 1$ * (A * Erec)
+R 1 * ( $1-\mathrm{A}$ ) * Ev * $\mathrm{Qsin} / \mathrm{Qp})$ )
Table B. 2 illustrates how this was then modelled in SimaPro. A combination of Iron scrap, unsorted $\{$ RoW\}| steel production, electric, low-alloyed $\mid$ APOS, $U$ (sorting) and Iron scrap, sorted, pressed $\{R E R\} \mid$ sorting and pressing of iron scrap $\mid$ Cut-off, $U$ (recycling) was used for Erec. Steel, chromium steel $18 / 8\{G L O\} \mid$ market for $\mid$ Cut-off, $U$ was used for Ev.

Table B.2: Example of the modelling according to the Circular Footprint Formula in SimaPro.

| Datasets | Amount | Unit |
| :--- | :--- | :--- |
| Iron scrap, sorted, pressed $\{$ RER $\} \mid$ sorting and pressing of iron scrap $\mid$ Cut-off, U | R1steel*Asteel*381*43/200 $=12.29$ | g |
| Iron scrap, unsorted $\{$ RoW $\} \mid$ steel production, electric, low-alloyed $\mid$ APOS, U | R1steel*Asteel $381 * 43 / 200=12.29$ | g |
| Steel, chromium steel $18 / 8\{\mathrm{GLO}\} \mid$ market for $\mid$ Cut-off, U | R1steel*((1-Asteel)*QsinQpsteel $) * 381 * 43 / 200=49.15$ | g |

In section 4.2.6, it was indicated that the system component paper towels included in the options handwashing and dry wiping were modelled according to the CFF. Table B. 3 provides an overview of the system components that were accordingly included for this process.

Table B.3: Overview of the system components that were included for modelling the system component paper towels according to the CFF.

| System components | Quantity | Unit | Source | Comment |
| :--- | ---: | :--- | :--- | :--- |
| Paper | 258.00 | g | Zampori \& Pant, 2019 |  |
| Paper (recycled content) | 36.55 | g | Zampori \& Pant, 2019 | Recycled content of tissue paper is 25\% |
| Recycling paper (for recycled content) | 43.00 | g | ecoinvent, 2019 | Sorting already included for paper recycling |
| Incinerating paper | 162.67 | g | Zampori \& Pant, 2019 |  |
| Electricity (retrieved from paper) | -0.77 | MJ | RVO, 2020; TNO, 2021 | Credits from End-of-Life, lower heating |
| Heat (retrieved from paper) | -0.67 | MJ | RVO, 2020; TNO, 2021 | value of paper is 20.7 MJ/kg |
| Disposal paper | 10.06 | g | Zampori \& Pant, 2019 |  |

## Appendix C: Uncertainty ranges of system configurations

Tables C.1, C. 2 and C. 3 contain the uncertainty ranges for each impact category of the different system configurations that are possible for the Customer cleaning, Retrieval and redistribution, and Professional cleaning stages of the life cycle of a reusable meal container system. For each option, the average absolute values that were included in the assessments and also in the tables in sections 4.2.6, 4.2.7 and 4.2.8 are included, and the lower and upper boundary values of the uncertainty ranges are indicated below them.

Table C.1: Lower and upper boundary values of the uncertainty ranges of the options for the Customer cleaning stage.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO ${ }_{2}$ eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Handwashing | $4.43 \mathrm{E}+01$ | $2.58 \mathrm{E}+00$ | $1.97 \mathrm{E}-07$ | $6.68 \mathrm{E}-04$ | $8.31 \mathrm{E}-03$ | $1.08 \mathrm{E}-02$ | $1.38 \mathrm{E}+00$ |
| Lower boundary | $4.32 \mathrm{E}+01$ | $2.51 \mathrm{E}+00$ | $1.91 \mathrm{E}-07$ | $6.59 \mathrm{E}-04$ | $8.25 \mathrm{E}-03$ | $1.08 \mathrm{E}-02$ | $1.38 \mathrm{E}+00$ |
| Upper boundary | 4.54 E | 2.6 | 2. | $6.76 \mathrm{E}-04$ | 8.38E-03 | $1.09 \mathrm{E}-02$ | 0 |
| Dishwashing | $1.98 \mathrm{E}+01$ | $8.65 \mathrm{E}-01$ | $9.27 \mathrm{E}-08$ | $2.41 \mathrm{E}-04$ | $4.62 \mathrm{E}-03$ | $4.43 \mathrm{E}-03$ | $3.70 \mathrm{E}-01$ |
| Lower boundary | $1.80 \mathrm{E}+01$ | $7.92 \mathrm{E}-01$ | $8.45 \mathrm{E}-08$ | $2.26 \mathrm{E}-04$ | $4.26 \mathrm{E}-03$ | $4.18 \mathrm{E}-03$ | $3.53 \mathrm{E}-01$ |
| Upper boundary | $2.17 \mathrm{E}+0$ | $9.38 \mathrm{E}-0$ | $1.01 \mathrm{E}-07$ | $2.55 \mathrm{E}-04$ | $4.98 \mathrm{E}-03$ | $4.69 \mathrm{E}-03$ | 88E |
| Dry wiping | $1.66 \mathrm{E}+01$ | $7.34 \mathrm{E}-01$ | $4.84 \mathrm{E}-08$ | $2.41 \mathrm{E}-04$ | $5.07 \mathrm{E}-03$ | $2.37 \mathrm{E}-03$ | 25 E |
| Lower boundary | $1.27 \mathrm{E}+01$ | $5.62 \mathrm{E}-01$ | $3.71 \mathrm{E}-08$ | $1.83 \mathrm{E}-04$ | $3.85 \mathrm{E}-03$ | $1.81 \mathrm{E}-03$ | $3.22 \mathrm{E}-01$ |
| Upper boundary | $2.06 \mathrm{E}+01$ | $9.06 \mathrm{E}-01$ | $5.97 \mathrm{E}-08$ | $2.98 \mathrm{E}-04$ | $6.28 \mathrm{E}-03$ | $2.94 \mathrm{E}-03$ | $5.27 \mathrm{E}-$ |
| Cold water rinsing | $1.03 \mathrm{E}+00$ | $6.22 \mathrm{E}-02$ | $5.89 \mathrm{E}-09$ | $2.08 \mathrm{E}-05$ | $4.42 \mathrm{E}-04$ | $1.09 \mathrm{E}-03$ | $1.43 \mathrm{E}-01$ |
| Lower boundary | $6.87 \mathrm{E}-01$ | $4.15 \mathrm{E}-02$ | $3.92 \mathrm{E}-09$ | $1.38 \mathrm{E}-05$ | $2.95 \mathrm{E}-04$ | $7.29 \mathrm{E}-04$ | $9.51 \mathrm{E}-02$ |
| Upper boundary | $1.37 \mathrm{E}+00$ | $8.30 \mathrm{E}-02$ | $7.85 \mathrm{E}-09$ | $2.77 \mathrm{E}-05$ | $5.89 \mathrm{E}-04$ | $1.46 \mathrm{E}-03$ | $1.90 \mathrm{E}-01$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use

Table C.2: Lower and upper boundary values of the uncertainty ranges of the scenarios for the Retrieval and redistribution stage.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO 2 eq | kg CFC-11 eq | kg C2 $\mathrm{H}_{4} \mathrm{eq}$ | kg SO 2 eq | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Scenario 1a | $7.16 \mathrm{E}+00$ | $4.42 \mathrm{E}-01$ | $3.18 \mathrm{E}-08$ | $1.92 \mathrm{E}-04$ | $3.77 \mathrm{E}-03$ | $1.62 \mathrm{E}-03$ | $1.26 \mathrm{E}-01$ |
| Lower boundary | $6.24 \mathrm{E}+00$ | $3.54 \mathrm{E}-01$ | $2.76 \mathrm{E}-08$ | $1.74 \mathrm{E}-04$ | $3.35 \mathrm{E}-03$ | $1.44 \mathrm{E}-03$ | $1.14 \mathrm{E}-01$ |
| Upper boundary | $8.08 \mathrm{E}+00$ | $5.30 \mathrm{E}-01$ | $3.59 \mathrm{E}-08$ | $2.09 \mathrm{E}-04$ | 4.18E-03 | $1.81 \mathrm{E}-03$ | $1.39 \mathrm{E}-01$ |
| Scenario 1b | $2.79 \mathrm{E}+01$ | $1.98 \mathrm{E}+00$ | $2.70 \mathrm{E}-07$ | $7.05 \mathrm{E}-03$ | $6.58 \mathrm{E}-03$ | $1.68 \mathrm{E}-03$ | $1.24 \mathrm{E}-01$ |
| Lower boundary | $1.98 \mathrm{E}+01$ | $1.40 \mathrm{E}+00$ | $1.91 \mathrm{E}-07$ | $4.98 \mathrm{E}-03$ | $4.65 \mathrm{E}-03$ | $1.19 \mathrm{E}-03$ | $8.74 \mathrm{E}-02$ |
| Upper boundary | $3.61 \mathrm{E}+01$ | $2.55 \mathrm{E}+00$ | $3.49 \mathrm{E}-07$ | $9.12 \mathrm{E}-03$ | $8.51 \mathrm{E}-03$ | $2.17 \mathrm{E}-03$ | $1.60 \mathrm{E}-01$ |
| Scenario 2a | $1.99 \mathrm{E}+01$ | $1.27 \mathrm{E}+00$ | $1.97 \mathrm{E}-07$ | $2.28 \mathrm{E}-04$ | $5.10 \mathrm{E}-03$ | $1.51 \mathrm{E}-03$ | $1.22 \mathrm{E}-01$ |
| Lower boundary | $1.78 \mathrm{E}+01$ | $1.13 \mathrm{E}+00$ | $1.76 \mathrm{E}-07$ | $2.03 \mathrm{E}-04$ | $4.55 \mathrm{E}-03$ | $1.35 \mathrm{E}-03$ | 1.09 |
| Upper boundary | $2.20 \mathrm{E}+01$ | $1.40 \mathrm{E}+00$ | $2.18 \mathrm{E}-07$ | $2.52 \mathrm{E}-04$ | $5.64 \mathrm{E}-03$ | $1.68 \mathrm{E}-03$ | $1.35 \mathrm{E}-01$ |
| Scenario 2b | $9.96 \mathrm{E}+00$ | $6.34 \mathrm{E}-01$ | $9.84 \mathrm{E}-08$ | $1.14 \mathrm{E}-04$ | $2.55 \mathrm{E}-03$ | $7.57 \mathrm{E}-04$ | $6.08 \mathrm{E}-02$ |
| Lower boundary | $8.89 \mathrm{E}+00$ | $5.66 \mathrm{E}-01$ | $8.79 \mathrm{E}-08$ | $1.02 \mathrm{E}-04$ | $2.28 \mathrm{E}-03$ | $6.77 \mathrm{E}-04$ | $5.43 \mathrm{E}-02$ |
| Upper boundary | $1.10 \mathrm{E}+01$ | $7.02 \mathrm{E}-01$ | $1.09 \mathrm{E}-07$ | $1.26 \mathrm{E}-04$ | $2.82 \mathrm{E}-03$ | $8.38 \mathrm{E}-04$ | $6.73 \mathrm{E}-02$ |
| Scenario 2c | $2.73 \mathrm{E}+00$ | $1.68 \mathrm{E}-01$ | $1.21 \mathrm{E}-08$ | $7.30 \mathrm{E}-05$ | $1.43 \mathrm{E}-03$ | $6.19 \mathrm{E}-04$ | $4.82 \mathrm{E}-02$ |
| Lower boundary | $2.38 \mathrm{E}+00$ | $1.35 \mathrm{E}-01$ | $1.05 \mathrm{E}-08$ | $6.64 \mathrm{E}-05$ | $1.28 \mathrm{E}-03$ | $5.49 \mathrm{E}-04$ | $4.33 \mathrm{E}-02$ |
| Upper boundary | $3.08 \mathrm{E}+00$ | $2.02 \mathrm{E}-01$ | $1.37 \mathrm{E}-08$ | $7.95 \mathrm{E}-05$ | $1.59 \mathrm{E}-03$ | $6.89 \mathrm{E}-04$ | $5.31 \mathrm{E}-02$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use
Table C.3: Lower and upper boundary values of the uncertainty ranges of the options for the Professional cleaning stage.

| Impact category | CED | GW | OLD | PO | AP | EP | WU |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit | MJ | kg CO 2 eq | kg CFC-11 eq | $\mathrm{kg} \mathrm{C} 2 \mathrm{H}_{4} \mathrm{eq}$ | $\mathrm{kg} \mathrm{SO}_{2} \mathrm{eq}$ | $\mathrm{kg} \mathrm{PO}_{4}{ }^{3-} \mathrm{eq}$ | $\mathrm{m}^{3}$ |
| Conventional dishwashing | $1.81 \mathrm{E}+01$ | $7.61 \mathrm{E}-01$ | $8.02 \mathrm{E}-08$ | $1.81 \mathrm{E}-04$ | $3.64 \mathrm{E}-03$ | $3.88 \mathrm{E}-03$ | $3.37 \mathrm{E}-01$ |
| Lower boundary | $1.62 \mathrm{E}+01$ | $6.88 \mathrm{E}-01$ | $7.20 \mathrm{E}-08$ | $1.67 \mathrm{E}-04$ | $3.28 \mathrm{E}-03$ | $3.63 \mathrm{E}-03$ | $3.20 \mathrm{E}-01$ |
| Upper boundary | $2.00 \mathrm{E}+01$ | $8.34 \mathrm{E}-01$ | $8.84 \mathrm{E}-08$ | $1.95 \mathrm{E}-04$ | $4.00 \mathrm{E}-03$ | $4.14 \mathrm{E}-03$ | $3.54 \mathrm{E}-01$ |
| Professional dishwashing | $1.22 \mathrm{E}+01$ | 5.15E-01 | $1.01 \mathrm{E}-07$ | $1.04 \mathrm{E}-04$ | 2.58E-03 | $1.91 \mathrm{E}-03$ | $2.21 \mathrm{E}-01$ |
| Lower boundary | $8.37 \mathrm{E}+00$ | $3.66 \mathrm{E}-01$ | $8.39 \mathrm{E}-08$ | $7.43 \mathrm{E}-05$ | $1.85 \mathrm{E}-03$ | $1.39 \mathrm{E}-03$ | $1.86 \mathrm{E}-01$ |
| Upper boundary | $1.60 \mathrm{E}+01$ | $6.64 \mathrm{E}-01$ | $1.17 \mathrm{E}-07$ | $1.33 \mathrm{E}-04$ | $3.32 \mathrm{E}-03$ | $2.43 \mathrm{E}-03$ | $2.56 \mathrm{E}-01$ |
| Industrial dishwashing | $6.15 \mathrm{E}+00$ | 2.98E-01 | $9.82 \mathrm{E}-08$ | $5.83 \mathrm{E}-05$ | $1.45 \mathrm{E}-03$ | $9.96 \mathrm{E}-04$ | $1.90 \mathrm{E}-01$ |
| Lower boundary | $5.73 \mathrm{E}+00$ | $2.81 \mathrm{E}-01$ | $9.63 \mathrm{E}-08$ | $5.53 \mathrm{E}-05$ | $1.37 \mathrm{E}-03$ | $9.39 \mathrm{E}-04$ | $1.86 \mathrm{E}-01$ |
| Upper boundary | $6.56 \mathrm{E}+00$ | $3.14 \mathrm{E}-01$ | $1.00 \mathrm{E}-07$ | $6.14 \mathrm{E}-05$ | $1.53 \mathrm{E}-03$ | $1.05 \mathrm{E}-03$ | $1.93 \mathrm{E}-01$ |

Legend impact categories: CED: Cumulative energy demand, GW: Global warming,
OLD: Ozone layer depletion, PO: Photochemical oxidation, AP: Acidification,
EP: Eutrophication, WU: Water use

## Appendix D: Stacked bar plots for the six meal container systems considered in this research

The six figures below provide illustrations of the percentual contributions of the impacts resulting from each life cycle stage to the total impact from the complete life cycle of the six different meal container systems that were assessed in section 4.5.3. From the figures, it can clearly be observed which of the life cycle stages contribute most to the total impact for each impact category.


Figure D.1: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the reusable PP box to the total environmental impact per impact category.


Figure D.2: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the reusable SS box to the total environmental impact per impact category.


Figure D.3: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the reusable GL box to the total environmental impact per impact category.


Figure D.4: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the single-use $P P$ box to the total environmental impact per impact category.


Figure D.5: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the single-use AL box to the total environmental impact per impact category.


Figure D.6: Stacked bar plot to illustrate the percentual contributions of each life cycle stage of the single-use $P A$ box to the total environmental impact per impact category.

