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Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup

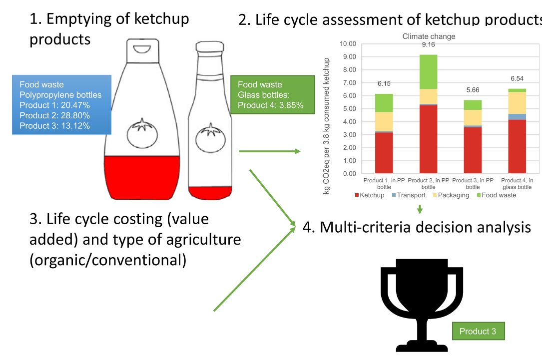
Bernhard Wohner [a,*], Viktoria Helene Gabriel [a,b], Barbara Krenn [a], Victoria Krauter [a], Manfred Tacker [a]

[a] Section Packaging and Resource Management, University of Applied Sciences Campus Vienna, Helmut-Qualtinger-Gasse 2/2/3, Vienna 1030, Austria
[b] Circular Analytics TK GmbH, Otto-Bauer-Gasse 3/13, Vienna 1060, Austria

HIGHLIGHTS

- Ketchup waste due to poor emptiability ranged from 3.85% (±0.41) to 28.80% (±3.30).
- Emptiability of ketchup in glass packaging is better than in polypropylene bottles.
- Glass packaging has greater environmental impacts than polypropylene bottles.
- Including packaging-related FLW can alter the ranking of products.
- Poor emptiability increases costs to the consumer but also economic value added.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a sustainability evaluation method for food-packaging systems is proposed. First, food waste due to poor emptiability was determined. Then, these quantities were included in life cycle assessments (LCA) and life cycle costing (value added, VA) of the products. Finally, LCA and VA results were combined using multi-criteria decision analysis, Technique for Order by Similarity to Ideal Solution (TOPSIS), in order to identify the most sustainable food packaging system.

As a case study, four different ketchup products were examined. For ketchup in polypropylene bottles, FLW resulting from poor emptiability ranged from 13.12% (±2.05) to 28.80% (±3.30) respectively, while this was only 3.85% (±0.41) for ketchup packaged in glass. After integrating the emptiability results into life cycle assessments, this resulted in greenhouse gas emissions of 5.66 to 9.16 kg CO_{2eq} per 3.80 kg consumed ketchup, the average consumption per capita in Austria. Importantly, poor emptiability of the examined products led to greater environmental impacts than the associated packaging. While greater product loss also pushes up the costs for consumers, it contributes to more value added to the economic system, which is in stark contrast to the goal of decoupling the economy from resource consumption.

Abbreviations: AC, acidification; CC, climate change; CNV, conventional agriculture; CRITIC, Criteria Importance through Intercriteria Correlation; EMPT, emptiability; FEU, eutrophication, freshwater; FLW, food losses and waste; FRD, resource use, fossils; FU, functional unit; GL, glass; LCA, life cycle assessment; MCDA, multi-criteria decision analysis; PP, polypropylene; ORG, organic agriculture; PEF, product environmental footprint; PM, particulate matter; TOPSIS, technique for order by similarity to ideal solution; VA, value added; WU, water use.

* Corresponding author.
E-mail address: bernhard.wohner@fh-campuswien.ac.at (B. Wohner).

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1. Introduction

Today, the world's economy is mainly based on a linear model. Recent studies suggest that globally, only 9% of all raw materials are reused, recycled or composted after their use (de Wit et al., 2018). Concerning the European Union (EU), only 67% of packaging and 46% of municipal waste is currently recycled (eurostat, 2019a). As a result, initiating a transformation towards a circular economy by adopting the 'Circular Economy Package' has become one of the top priorities of the EU (European Commission, 2019b).

This package includes goals such as requiring full recyclability or reusability of packaging (European Commission [DG ENV - Directorate C], 2018), increased recycling quotas of packaging as well as halving food waste by 2050 or 2030 respectively (The European Parliament and the Council, 2018). In Austria, only 25% of plastic packaging is currently recycled (Altstoff Recycling Austria AG, 2018), meaning that this must be approximately doubled by 2030 to fulfill the mandatory quota of 55%.

As a possible solution, in addition to increasing the recyclability of plastic packaging, a general reduction of plastic is highly discussed. Such a reduction has further gained fresh prominence due to increasing public disdain concerning plastic. This has been addressed by several Austrian food retailers, who declared the reduction of plastic packaging in their mission statements (HOFER, 2018; REWE Group, 2018; SPAR, 2019). Furthermore, the reduction of plastic packaging by 20% to 25% was officially declared a goal of the Austrian government in 2018 (Bundeskanzleramt, Bundesministerium Öffentlicher Dienst und Sport, Bundesministerium Nachhaltigkeit und Tourimus, 2018). However, environmental benefits of reducing the quantity of plastic packaging could even lead to greater environmental impacts when it is substituted by other materials such as paper, glass or metal (Pilz et al., 2010). Furthermore, a reduction or substitution of plastic packaging could increase the generation of food loss and waste (FLW) (Pauer et al., 2019; Wohner et al., 2019a). While much research has been carried out on the evaluation of direct environmental impacts of packaging by conducting life cycle assessments (LCA), there is still very little scientific understanding of indirect effects (Molina-Besch et al., 2018; Wohner et al., 2019a). Since protecting food is in fact the main function of packaging (Lindh et al., 2016; Pauer et al., 2019), sustainability evaluations of packaging should not be carried out without considering its impact on the filling good and thus of holistic evaluations of food together with its associated packaging (food-packaging systems) (Pauer et al., 2019). With 14% of food being lost between post-harvest and retail level (FAO, 2019) together with older estimates of 30% being lost across the whole supply chain (Gustavsson et al., 2011), it is clear however that FLW and therefore indirect effects of packaging are a pressing concern. Several authors already focus on assessing FLW by using LCA (Beretta and Hellweg, 2019; Scherhaufer et al., 2018), with an increasing number of authors integrating FLW into the LCA of packaging (Molina-Besch et al., 2018). Among other aspects, this includes (i) FLW related to packaging being difficult to empty (Meurer et al., 2017; Williams et al., 2012; Williams and Wikström, 2011; Wohner et al., 2019b), (ii) calculation of break-even rates between the volume of packaging material and FLW (Bacenetti et al., 2018; Yokokawa et al., 2018) or (iii) modelling the quantity of FLW based on shelf life (Conte et al., 2015).

According to Pauer et al. (2019), evaluations of food-packaging systems should include direct and indirect environmental effects, in addition to circularity assessments, yet without proposing a combined evaluation method. Niero and Kalbar (2019) already combined direct environmental effects (LCA results) of packaging and circularity metrics using multi-criteria decision analysis (MCDA). In context of this research, however, we argue that circularity parameters such as recycled content or recycling quotas may affect LCA results, thus violating the rules of using only independent attributes in MCDA (Belton and Stewart, 2003).

In summary, the aim of the present paper is to analyze packaging-related FLW of food-packaging systems in order to integrate it into environmental and economic assessments. Against this background, a case study on tomato ketchup is conducted. Emptiability is quantified, which is then integrated into LCA and life cycle costing (LCC) of the products. Finally, the most sustainable product is identified by using multi-criteria decision analysis (MCDA).

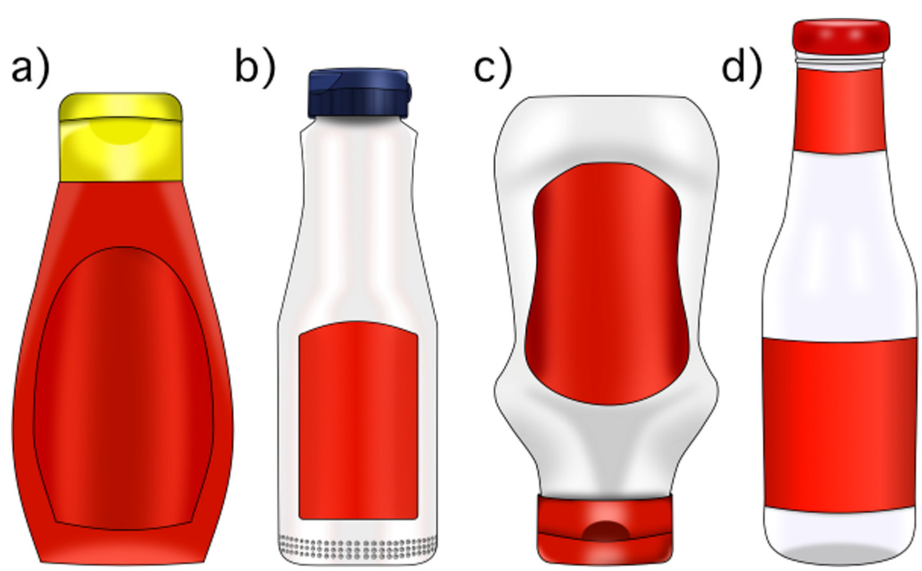

Fig. 1. Ketchup products chosen as illustrative examples. a) Conventional ketchup, produced in Austria, 450 g indicated filling quantity, 29.99 g colored polypropylene (PP) bottle with 10.81 g colored PP cap, 0.28 g multilayer seal (assuming a composition of 52% polyethylene, 25% polyethylene terephthalate, 17% adhesive and 6% aluminum) and 0.97 g PP labels. 172 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-450-CONV). b) Organic ketchup, produced in Austria, 380 g indicated filling quantity, 22.30 g clear transparent PP bottle with 4.36 g colored PP cap, 0.29 g multilayer seal and 0.63 g PP labels. Sales price: 2.99 € (PP-380-ORG). c) Organic ketchup, produced in the Czech Republic, 550 g indicated filling quantity, 30.96 g clear transparent PP bottle with 9.79 g colored PP cap, 0.32 g multilayer seal and 1.27 g paper labels. 210 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-550-ORG). d) Organic ketchup, produced in Italy, 480 g indicated filling quantity, 236.61 g flint packaging glass with 4.88 g tinplate screw cap and 1.29 g paper labels. 225 g tomatoes per 100 g ketchup. Sales price: 1.45 € (GL-480-ORG).

2. Materials and methods

In this section, we first present the case study. Based on this, selected criteria and their quantification is discussed. Finally, the selection and calculation of a suitable method for the sustainability evaluation is presented.

2.1. Case study: tomato ketchup

Tomato ketchup was chosen as a case study. Ketchup is made from fresh tomatoes or tomato puree, sugar and/or sweetener, spices and seasoning, salt and vinegar. The final product must have a minimum of 28% dry mass (Bundesministerium für Arbeit, Soziales, Gesundheit und Konsumentenschutz, 2015). In Austria, 3.8 kg of ketchup is consumed per capita and year (Statista GmbH, 2019).

The following products of different brands were purchased at various supermarket chains (Fig. 1):

2.2. Life cycle assessment

Life cycle assessment is a well-known method to assess environmental impacts across the life cycle of a product, frequently used in food and food packaging studies (Fraval et al., 2019). LCA for this article was based on ISO 14040 (ISO, 2006a) with additional guidance from the Product Environmental Footprint (PEF) (European Commission, 2017), which is being currently developed by the European Commission. In contrast to ISO 14040, the PEF guidance includes stricter recommendations. For this study, the PEF guidance was used for:

- Selection of life cycle impact categories
- Identification of the most relevant life cycle impact categories
- Default transport distances
- Allocation regarding input and output of secondary materials

Calculations were performed using OpenLCA and the Ecoinvent 3.5 database. LCA for the case study was limited to secondary data only. This type of LCA method can be considered as 'streamlined LCA', which has the benefit of reducing the expenditure of time and resources (Speck et al., 2015).

2.2.1. Functional unit, reference flow and system boundaries

The functional unit (FU) was defined as 'consumption of 3.8 kg ketchup'. This led to different reference flows for the examined products, determined by the loss of ketchup due to poor emptiability. As an example, if 50% of food loss and waste (FLW) occurs at the consumer, all environmental impacts up to the point of loss are doubled (Wikström et al., 2014). System boundaries and the resulting presented life cycle stages include:

- Packaging: Raw materials, manufacturing of glass and plastic bottles, transport of empty bottles to the ketchup production site, disposal of packaging
- Ketchup processing: Cultivation of tomatoes and sugar, thermal and electrical energy used in the production of ketchup
- Transport of the final product to an Austrian supermarket
- Transport of the final product from the supermarket to the home of the consumer
- Food loss and waste: Calculated as the difference between provisioned and consumed ketchup

2.2.2. Life cycle inventory of packaging manufacturing

Ketchup bottles were first emptied (see Section 2.2.8) before the packaging was disassembled and weighed. Packaging manufacturing was then modelled using Ecoinvent datasets, taking the respective datasets for the raw materials and their manufacturing processes. No recycled content was assumed for plastic packaging and 40% for flint glass bottles (European Commission, 2019a). Transport distances between the packaging manufacturers to the ketchup production site were assumed to be (i) 230 km by truck, (ii) 280 km by train and (iii) 87 km by ship for plastic bottles. For glass bottles a transport of (i) 350 km by truck, (ii) 39 km by train and (iii) 87 km by ship was chosen (European Commission, 2017).

2.2.3. Life cycle inventory of agricultural production

For the life cycle inventory of ketchup, the quantity of tomatoes used in processing was taken from the label. From this, the quantity of added sugar was calculated after subtracting the stated sugar content from the sugar contained in the tomatoes, assuming a sugar content of 2.6% and a water content of 95% of the average fruit (USDA, 2019). Among the examined products were ones of organic and conventional agriculture. Organic farming is often associated with reduced farm inputs and higher soil carbon sequestration, therefore reducing environmental impacts compared to conventional agriculture. However, there is an ongoing debate concerning the actual sustainability of organic agriculture, since this agricultural practice often leads to lower yields, which increases greenhouse gas emissions in some cases (Smith et al., 2019). Regarding tomatoes, organic agriculture may have lower (He et al., 2016; Ronga et al., 2019) or higher yields (Stanhill, 1990), which in turn leads to lower (He et al., 2016) or higher (Ronga et al., 2019; Vermeulen and CJM, 2011) environmental impacts compared to conventional tomatoes. Moreover, comparative LCA studies of organic and conventional agriculture are not always able to capture the differences (Meier et al., 2015). For this paper, it was assumed that organic agriculture is a beneficial concerning sustainability due to it having multiple ecological and social benefits, such as greater biodiversity and fewer potential negative effects on human health (Shennan et al., 2017). Nonetheless, there is no Ecoinvent dataset available for organic tomatoes. Since the impact of organic agriculture could not be considered in the LCA, it was included as an additional criterion. Quantification of organic agriculture was carried out by assigning a value of '1' for products of organic, and a value of '0' for products of conventional agriculture. Other ingredients of tomato ketchup such as vinegar and spices were excluded from the analysis due to their small and unknown quantities.

2.2.4. Life cycle inventory of ketchup processing

In the manufacturing process of ketchup, tomatoes are heated with steam to up to 99 °C (Amón et al., 2015). Thermal energy consumption of this process was calculated as the product of the latent heat of vaporization of water at 100 °C (2.26 MJ/kg) and the volume of water needed to be evaporated to achieve the final water content of the respective ketchup. This water content was estimated as the difference between 100% and the sum of carbohydrates, fat, protein and assumed average ash content of 3% (Sharoba et al., 2005). It was assumed that waste heat is not recovered (Amón et al., 2015). The electricity consumption of ketchup manufacturing was taken from existing literature (Andersson et al., 1998). Country-specific electricity mixes and transport distances to Austria were considered, with a modal split of 75% lorry and 25% freight train (eurostat, 2019b) (eurostat, 2019b) for international transports. The following distances for the transport of the final products between productions sites and Austrian retail were estimated:

- Ketchup produced in Austria: 200 km
- Ketchup produced in the Czech Republic: 375 km
- Ketchup produced in Italy: 950 km

2.2.5. Transports of final products

The transport of the final products between the supermarket and the home of the consumer was assumed to be 5 km, of which 62% were allocated to a passenger car with a trunk of load of 200 l, 5% to a van and 33% were not allocated (Castellani et al., 2018; European Commission, 2019a). As a result, the distribution of 1 l ketchup is associated with 0.0155 km driven by passenger car.

A summary of data concerning the modelled foreground system is presented in Table 1.

2.2.6. Selection of impact categories

Initially, all 16 impact categories recommended by PEF (Castellani et al., 2018) were calculated. Then, the PEF guidance was followed for the selection of the most relevant impact categories.

First, all impact categories were normalized, meaning that their magnitude of relative to a reference information (ISO, 2006b) (in the context of PEF the impacts of an average world citizen per year) were calculated. Next, the normalized values were weighted using the values provided by the PEF guidance. Accordingly, the three toxicity impact categories shall not be used for benchmarking with assigned weights of 0%, since their methodology is not yet considered as robust enough. Finally, the most relevant impact categories were identified based on the ones that contribute at least 80% to the total sum (European Commission, 2017). Relevant impact categories were the same for all products. This is also true for their order of contribution except for GL-480-ORG, where the ranks of particulate matter and acidification are swapped (Table 2).

Consequently, results of the most relevant impact categories per functional unit are used as criteria in the MCDA. Normalized and weighted results were only used for the procedure of selecting the most relevant impact categories. Results of all impact categories, their respective contribution to the total, as well as normalization and weighting factors are listed in the supplementary material.

2.2.7. End-of-life and allocations

The use of recycled content and the disposal of the packaging was modelled according to the Circular Footprint Formula listed in the PEF guidance (European Commission, 2017). Energy savings of 2.5% per 10% recycled content are assumed for the production of glass bottles (Stettler et al., 2016). Life cycle inventory data of plastic recycling processes in Austria was taken from literature (van Eygen et al., 2018b), with quality factors of recyclate of 1.00 for glass and metal (European Commission, 2019a), as well as 0.67 for polypropylene (calculated as the average ratio of market prices between September 2018 and 2019 (plasticker et al., 2019)).

For this article, it was assumed that PP bottles contaminated with ketchup can be recycled. However, this might not be true since ketchup residues may affect the sorting and/or recycling process as has been shown for PET bottles (Boesveld, 2011). It was assumed that all PP bottles consist of 5% by weight of ethylene vinyl alcohol (Hedenqvist, 2018), which still allows the bottle to be recycled (FH Campus Wien, 2019). Consequently, the only non-recyclable packaging components were multilayer seals and paper labels.

Recycling rates in Austria are 14% for polypropylene bottles (van Eygen et al., 2018a), 84% for glass and 86% for metal packaging (eurostat, 2019c). Polypropylene caps are currently not recycled in Austria (van Eygen et al., 2018a). Due to landfill restrictions in Austria (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2008), only non-recycled quantities of metal and glass packaging were assumed to be landfilled, while non-recycled plastic packaging was assumed to be incinerated.

2.2.8. Indirect environmental effects due to FLW

Quantifying packaging-related FLW is challenging (Wohner et al., 2019a) and therefore often omitted in studies of food-packaging systems (Molina-Besch et al., 2018). In a previous study we proposed a method for testing dairy products on their 'technical emptiability' and its integration in LCA studies (Wohner et al., 2019b) as a possibility to measure packaging-related FLW. For the present case study, not only technical but also practical emptiability was tested. Finally, the results of practical emptiability were taken to calculate the respective reference flows of the investigated products associated with the functional unit.

Practical emptiability simulates an average emptying behavior by the consumer. For plastic bottles, first the bottles were shaken three times and squeezed until air was released. Next, the bottles were swiveled and then squeezed again until air was released. This step was repeated three times. Glass bottles were shaken three times and then held upside down for 2 min. Subsequently, the bottles were shaken three times and then held upside for 1 min.

Technical emptiability represents the best possible emptying procedure without damaging the packaging. For this, both glass and plastic bottles including their caps were scraped with a dedicated ketchup spoon (length of 24.5 cm) after practical emptiability tests.

Finally, the emptiability index was expressed as the ratio of ketchup left in the bottle to the original filling quantity. Testing was performed at room temperature (22 °C ± 1). Based on previous studies, a sample size of 6 was taken to assure significant results (Meurer et al., 2017; Wohner et al., 2019b).

2.3. Economic assessment

Life cycle costing is an approach often used for the economic evaluation of a product. 'Conventional' LCC represents the historic practice of economic assessments, which includes costs associated with a product and which are generally presented only from one, the producer's or consumer's, perspective (Hunkeler et al., 2008). Further, conventional LCC is often performed not all along the entire supply chain, often excluding End-of-Life operations. In contrast, 'environmental LCC' is performed alongside LCA, using the same system boundaries and models and thus covering the whole life cycle of a product. Moreover, by including the full life cycle, environmental LCC enables the economic evaluation of a product from a system's perspective. Therefore, according to Hunkeler et al. (2008), environmental LCC should be the approach of choice for sustainability assessments. Hence, the economic evaluation in this paper is conducted taking the 'value added' approach (VA). Generally, the revenues (R) for selling a product are higher than its production costs (C) (Heijungs et al., 2013), resulting in a margin which is referred to as "added value", given in a monetary unit, in this study Euro (€).

$$VA = R - C$$

Consequently, the total life cycle cost is the "sum of all value added over the life cycle" (Moreau and Weidema, 2015). Since environmental impacts are already covered by the LCA, their associated costs are not included in VA, as this would be considered as double-counting.

In this paper, VA is calculated following the same principles as for the LCA. Therefore, the final VA result is the sum of value added by the production and disposal of ketchup, its packaging and all related transport, with additional consideration of the final sales price. This can be expressed as follows:

$$VA_{Total} = VA_{IN} - C_{IN} + VA_{EN} - C_{EN} + VA_{PA} - C_{PA} + VA_{TR} - C_{TR} + R_{PU} - C_{PU} + VA_{EoL}$$

where:

- VA_{Total}: Total VA of the respective product
- VA_{IN}: VA of agricultural production of ingredients (tomatoes and sugar) (calculated as the total of the difference between costs for producing and revenues of selling tomatoes or sugar, and the VA for all upstream processes)
- C_{IN}: Costs to the ketchup producer for purchasing ingredients
- VA_{EN}: VA of thermal and electrical energy production (calculated as the total of the difference between costs for producing and revenues of selling energy, and the VA for all upstream processes)
- C_{EN}: Costs to the ketchup producer for purchasing energy

Table 1
Summary of data for modelling the foreground system. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture. Data are given per kg produced and distributed ketchup. Remaining abbreviations represent: PP, polypropylene; vkm, vehicle-kilometer; tkm, ton-kilometer.

		Unit	PP-450-CNV	PP-380-ORG	PP-550-ORG	GL-480-ORG
Ingredients	Tomatoes	kg	1.72	2.85	2.10	2.25
	Added sugar	kg	0.14	0.15	0.09	0.16
Energy consumption for processing	Electricity	MJ	0.38	0.38	0.38	0.38
	Thermal energy (steam)	MJ	2.34	4.82	2.97	3.62
Packaging	PP bottle (blow moulded)	g	66.50	59.17	55.60	0
	Glass bottle	g	458.84	0	0	0
	PP cap (injection moulded)	g	23.97	11.57	17.58	0
	Tinplate cap	g	0	0	0	9.46
	Multilayer seal	g	0.62	0.77	0.57	0
	PP label	g	2.15	1.67	0	0
	Paper label	g	0	0	2.28	2.50
Transport from manufacturer to retail	Lorry	tkm	0.22	0.21	0.30	1.03
	Freight train	tkm	0	0	0.10	0.37
Transport from retail to consumer	Passenger car	vkm	0.014	0.019	0.014	0.014
	Van	tkm	0.0001	0.0001	0.0001	0.0002

- VA_{PA}: VA of packaging production (calculated as the total of the difference between costs for producing and revenues for selling packaging, and the VA for all underlying processes)
- C_{PA}: Costs to the ketchup producer for purchasing packaging
- VA_{TR}: VA of transports (calculated as the total of difference between costs and revenues for providing transport, and the VA for all upstream processes)
- C_{TR}: Costs to the ketchup producer for the transport of products
- R_{PU}: Revenue to the ketchup producer for selling ketchup to the consumer
- C_{PU}: Costs to the consumer for purchasing ketchup from the producer
- VA_{EOL}: VA of disposal of ketchup and packaging (calculated as the total of the difference between costs and revenues of recycling or incineration of ketchup or packaging, and the VA for all upstream processes)

For the calculation, default values available in the Ecoinvent 3.5 database version of OpenLCA were taken (Ciroth, 2016a). In OpenLCA, prices already contained but hidden in several Ecoinvent datasets were made visible by the software publisher, with information on costs added to further datasets (Ciroth, 2016b). Similar to the conducted LCA, a major limitation is that possible differences between organic and conventional tomatoes could not be considered due to a lack of data in Ecoinvent.

2.4. Multi-criteria decision analysis

2.4.1. Selection and calculation

The examined products show different results between LCA impact categories, as well as between LCA and VA results in general. Hence, the need for a method to decision making tool arises, able to solve multi-dimensional issues. In this context, multi-criteria decision analysis methods are increasingly used to identify the best possible solution out of several alternatives (Wątróbski et al., 2019a). Based on the listed criteria, a suitable MCDA method was defined as being able to (i) take different weights into account, (ii) compare criteria on a quantitative scale and (iii) generate a ranking. Using the MCDA tool (Wątróbski et al., 2019b), TOPSIS (Hwang et al., 1993) was identified as a method meeting these requirements. The following terms are defined for better readability and are frequently used in MCDA:

- Alternative: Several predetermined, limited and independent alternatives. For this study, these are the four examined products (Alinezhad and Khalili 2019).
- Criterion: A particular perspective according to which alternatives may be compared (Belton and Stewart, 2003). In the context of this study, these are comprised of the six chosen LCA impact categories and the VA.
- Attribute: a "quantitative or qualitative measure of performance associated with a particular criterion" (Belton and Stewart, 2003), which can be either beneficial (with the goal of maximization) or non-beneficial (with the goal of minimization). In this study, the attributes are the results of VA and the chosen LCA impact categories, with the former considered as being beneficial, and the latter as being non-beneficial.
- Normalization: Converting attributes into non-dimensional form to allow their aggregation into a final score (Jahan and Edwards, 2015; Vafaei et al., 2016)

The general calculation steps of TOPSIS can be summarized as follows (ÇELEN, 2014; Hwang et al., 1993; Kumar et al., 2017):

Table 2
Most relevant life cycle impact categories, in descending order of their relevance.

Impact category	Indicator	Unit	Life cycle impact assessment method
Climate change (CC)	Radiative forcing as Global Warming Potential (GWP100)	kg CO_{2eq}	IPCC 2013 (IPCC, 2013)
Resource use, fossils (FRD)	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Bruijn et al., 2004)
Water use (WU)	User deprivation potential (deprivation-weighted water consumption)	m^3 $world_{eq}$	Available Water Remaining (AWARE) (UNEP, 2016)
Eutrophication, freshwater (FEU)	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Goedkoop et al., 2013)
Acidification (AC)	Accumulated Exceedance (AE)	mol $H+_{eq}$	Accumulated Exceedance (Posch et al., 2008)
Particulate matter (PM)	Impact on human health	Disease incidence	PM method (UNEP, 2016)

1. Creation of a decision matrix

$$X = (x_{ij})_{mxn}$$

consisting of m alternatives ($A_1, A_2, \ldots, A_m$) and n criteria ($C_1, C_2, \ldots, C_n$), with the intersection of each alternative and criteria given as x_{ij}.

2. Normalization of the decision matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$

3. Calculation of the weighted normalized decision matrix by multiplication of the normalized matrix with the attribute's weights (w_j):

$$v_{ij} = w_j * r_{ij},$$

$i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$where $w_j = \frac{W_j}{\sum_{i=1}^{n} W_i}$ j = 1, 2, …, n

4. Determination of worst alternative A_w (or negative ideal solution) and best alternative A_b (or positive ideal solution):

$$A_w = \{\langle \max(v_{ij} | i = 1, 2, \ldots, m) | j \in J_- \rangle, \langle \min(v_{ij} \mid i = 1, 2, \ldots, m) | j \in J_+ \rangle\} \equiv \{v_{wj} \mid j = 1, 2, \ldots, n$$

$$A_b = \{\langle \min(v_{ij} | i = 1, 2, \ldots, m) | j \in J_- \rangle, \langle \max(v_{ij} \mid i = 1, 2, \ldots, m) | j \in J_+ \rangle\} \equiv \{v_{bj} \mid j = 1, 2, \ldots, n,$$

where for beneficial attributes:

$$J_+ = \{j = 1, 2, \ldots, n \mid j,$$

and for non-beneficial attributes:

$$J_- = \{j = 1, 2, \ldots, n \mid j$$

5. Calculation of the Euclidean distance of each alternative to the worst (d_{iw}) and best solution (d_{ib}):

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{wj})^2}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{bj})^2}$$

where $i = 1, 2, \ldots, m$

6. Calculation of the relative closeness (CC_i) of each alternative to the ideal solution:

$$CC_i = \frac{d_{iw}}{d_{iw} + d_{ib}}$$

7. Ranking of the alternatives according to CCi (i = $1, 2, \ldots, m$)

Individual calculation steps of TOPSIS for the case study are listed in the supplementary material.

2.4.2. Determination of weights

Determination of criteria weights is equally crucial and controversial since there is an abundant number of methods regarding this procedure which all produce different results and thus considerably influence the outcome of an MCDA. Such methods can be classified either (i) a priori, where weights are determined before data is collected, or (ii) a posteriori, were the determination of weights occurs after data collection. While a priori weights are generally elicited by expert interviews or questionnaires, a posteriori weights are calculated based on the collected data for each alternative (Kao, 2010).

For this paper, three weighting sets were calculated and used for TOPSIS, namely (i) equal weighting, (ii) Criteria Importance through Intercriteria Correlation (CRITIC) (Diakoulaki et al., 1995) and (iii) entropy (Li et al., 2011), similar to a sustainability assessment of biodiesel (Anwar et al., 2019).

2.4.2.1. Equal weighting. Equal weighting is the simplest type of weighting method, in which each criterion is given the same importance. In this study, 8 criteria were selected, which results in a weight (w_j) of 12.5% per criteria.

$$w_j = \frac{1}{8}$$

2.4.2.2. Weights of criteria using CRITIC. Calculating weights using CRITIC is performed by characterizing each vector by its standard deviation and a subsequent construction of a symmetric matrix with linear correlation coefficients between the vectors (Alinezhad and Khalili 2019).

First, the decision matrix is normalized as follows:

$$x_{ij} = \frac{r_{ij} - r_i^-}{r_i^+ - r_i^-}$$

$$x_{ij} = \frac{r_{ij} - r_i^+}{r_i^- - r_i^+},$$

where $i = 1, \ldots, m$ and $j = 1, \ldots, n$ and x_{ij} representing the normalized value for alternative i and attribute j, with

$$r_i^+ = \max(r_1, r_2, \ldots, r_m)$$

$$r_i^- = \min(r_1, r_2, \ldots, r_m)$$

Then, the correlation coefficient between attributes is calculated as follows:

$$\rho_{jk} = \frac{\sum_{i=1}^{m} (x_{ij} - \overline{x_j})(x_{ik} - \overline{x_k})}{\sqrt{\sum_{i=1}^{m} (x_{ij} - \overline{x_j})^2 \sum_{i=1}^{m} (x_{ik} - \overline{x_k})^2}}.$$

with $\overline{x_j}$ and $\overline{x_k}$ representing the mean of jth and kth attributes, calculated as

$$\overline{x}_j = \frac{1}{n} \sum_{j=1}^{n} x_{ij}$$

$$\overline{x}_k = \frac{1}{n} \sum_{k=1}^{n} x_{ik},$$

where i = 1, 2, …, m.

After that, the standard deviation of each attribute is calculated as

$$\sigma_j = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_{ij} - \overline{x}_j)2},$$

where $i = 1, \ldots, m$.

Next, the index (C) is calculated as:

$$C_j = \sigma_j \sum_{k=1}^{n} \left(1 - \rho_{jk}\right)$$

Finally, the weight of attributes is derived by:

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j}$$

2.4.2.3. Weights of criteria using entropy. First, the decision matrix is normalized as follows:

$$\overline{r_{ij}} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}},$$

where $j = 1, 2, \ldots, n$ and $\overline{r_{ij}}$ is the normalized value of the decision matrix.

Then, the degree of entropy is determined:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \overline{r}_{ij} \ \ln \overline{r}_{ij},$$

where $j = 1, 2, \ldots, n$ and $0 < E_j < 1$.

Next, the deviation rate is calculated by:

$$d_j = 1 - E_j,$$

where $j = 1, 2, \ldots, n$.

Finally, weights of attributes are derived by:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

3. Results and discussion

3.1. Emptiability

Practical emptiability of the examined bottles ranges from 3.85% (± 0.41) to 28.80% (±3.30), while this can be substantially reduced to between 3.37% (±0.29) and 7.08% (±0.61) when a spoon is used ('technical emptiability') (Fig. 2). Variability was calculated as 95% confidence intervals.

In previous studies, the emptiability index of ketchup was reported as 0.5% to 26% (Andersson et al., 1998) in PP bottles and 30% to 52% (Boesveld, 2011) in PET bottles, which shows that the quantity of ketchup remaining in the package can even be higher.

From the figure above (Fig. 2), it is apparent that the product in a glass bottle (GL-480-ORG) has the best emptiability. In contrast, PP-380-ORG has the poorest. Important to emphasize is that emptiability is a function of both product and packaging, thus not allowing the generalization of glass being better than plastic packaging, since the products in different packages were not identical. Emptiability is mainly influenced by the packaging geometry, the surface tension of food and packaging, and particularly by the viscosity of food (Schmidt, 2011). Besides processing conditions, viscosity of ketchup increases with its tomato content. Since the product with the highest tomato content yielded the worst emptiability, this may result in being one of the major drivers of FLW. One major limitation here is that the portioning behavior of the products could not be considered. With the glass bottle, dosing may be more difficult than with the plastic bottles. This could lead to the consumer emptying more ketchup than required which may ultimately result in disposing of it.

Statistical analysis was performed using one-way ANOVA (Fisher's with Tukey post hoc test for samples with equality of variances and Welch's with Games-Howell post hoc test for samples without equality

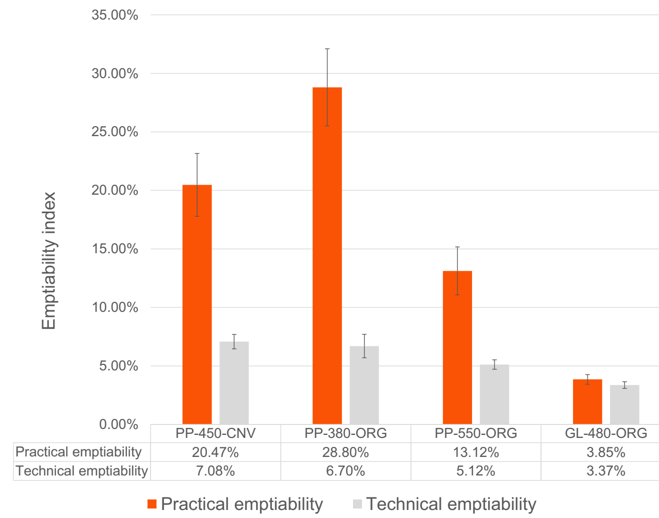

Fig. 2. Emptiability results of examined ketchup products. Bars represent the mean, while error bars are 95% confidence intervals ($n = 6$). Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

of variances), after testing for normality with Shapiro Wilk tests. All statistical tests were performed with the software 'Jamovi' (version 1.1.7) (The jamovi project, 2019) and can be found in the supplementary material.

3.2. LCA results

Climate change results of all products (Fig. 3a) range from 5.66 to 9.16 kg CO_{2eq} per functional unit (FU) respectively. Packaging is responsible for 24% to 26% of the total for PP-450-CNV, PP-550-ORG and GL-480-ORG, but only 12% for PP-380-ORG due to its high tomato content and poor emptiability (Fig. 3a-f). In other impact categories, plastic packaging contributes 7% to 13% and glass packaging 29% to 31% to the overall result. Obviously, direct environmental impacts of glass packaging are associated with greater environmental impacts than plastic bottles, which is well in line with results of other LCA studies (Boesen et al., 2019; Humbert et al., 2009; Niero and Kalbar, 2019). Nonetheless, this is compensated for by its good emptiability.

Concerning the total LCA results, the most influential factors are FLW, the tomato content and the resulting thermal energy required for water vaporization. Regarding water use, cultivation of tomatoes is almost solely responsible for environmental impacts. Taken together, production and loss of food is substantially more relevant than its associated packaging concerning environmental impacts. By contrast, transport is of relatively low importance. One interesting outcome is that LCA results of PP-550-ORG are better than PP-450-CNV, which would not be the case if FLW would have been excluded. This finding underlines the value of quantifying and integrating packaging-related FLW into life cycle assessments.

Detailed LCA results and results of the remaining calculated impact categories are listed in the supplementary material.

3.3. Value added results

Value added results for the investigated products (Fig. 4) show a similar picture to that of the LCA results with the important difference that here, higher values are considered as beneficial. Therefore, VA results are in fact diametrically opposed to most of the impact categories of the performed LCA. This arises mostly from the effect that a greater material intensity leads to more value added along the supply chain,

Fig. 3. Life cycle assessment results of most relevant impact categories for ketchup. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

which contradicts the goal of eco-economic decoupling (European Commission, 2011).

Consequently, since the sales price of a product is higher than its production costs, poorer emptiability also leads to a greater VA result. For PP-380-ORG, this is particularly clear, since it has the highest tomato content as well as the poorest emptiability. Furthermore, the calculated margin regarding the sales price for this product is substantially greater compared to the others. This is confirmed by other studies indicating that smaller packages generally generate higher revenues than larger ones (Yonezawa and Richards, 2016).

In contrast, GL-480-ORG, is not only the one with the lowest sales price per kg, but also the one with the best emptiability, leading to the worst VA results in comparison. Using conventional LCC and taking the consumer's perspective, the results would be exactly the other

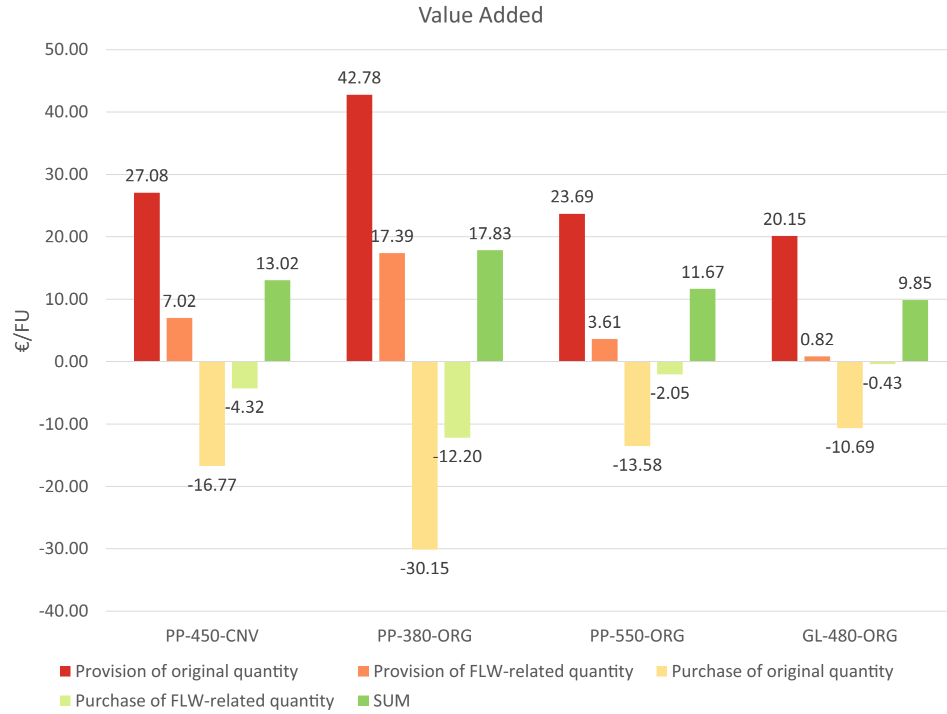

Fig. 4. Value added results. Original quantity is 3.8 kg of ketchup, while the quantity due to food loss and waste (FLW) is generated by the respective emptiability of the products. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

way around. Costs to the consumer for eating 3.8 kg ketchup would be 42.35 € for PP-380-ORG, but only 11.12 € for GL-480-ORG. In turn, from the manufacturer's point of view, a higher loss would be preferable as the quantity sold would increase. As Wood and Hertwich (2013) point out, life cycle costing results should generally be maximized from society's perspective to generate economic growth but minimized from an individual's perspective to save costs. Consequently, we agree with Heijungs et al. (2013) who raised the question: "What do we in fact want to learn from life cycle costing"?

We conclude that taking a system's perspective is more relevant in the context of sustainability assessments than taking an individual's perspective. Thus, despite its limitations, we still consider VA as a suitable method for performing environmental LCC together with LCA. Nonetheless, ff this debate is to be moved forward, methods portraying a broader economic scope should be developed. Previous research has already demonstrated how not only economic growth, but also characteristics such as consumer satisfaction, business diversity or long-term investments could be considered in new methods concerning life cycle costing (Neugebauer et al., 2016).

3.4. Sustainability evaluation using TOPSIS

After determining LCA and VA results, the decision matrix for TOPSIS was created (Table 3).

Next, weights were calculated based on the approaches of equal weighting, CRITIC and entropy (Table 4) described in Section 2.4.2.

Using CRITIC, VA and organic agriculture are given more, LCA results less weight compared to equal or entropy weights.

Finally, after following the calculation steps laid out in Section 2.4.1, the final closeness values using TOPSIS were determined, with the most sustainable food-packaging system being the one closest to '1.00' (Fig. 5).

Closeness values of the products differ greatly depending on the chosen weighting set. Nonetheless, PP-550-ORG performs best concerning all three weighting sets, which is followed by GL-480-ORG. The most striking observation is the difference in performance of PP-380-ORG and PP-450-CNV, which is the consequence of the higher importance of LCA results in the entropy and organic agriculture in the CRITIC weighting set. As discussed in Section 3.3, VA increases with material intensity and FLW. If TOPSIS were calculated with life cycle costs from the consumer's perspective, this would have a positive impact on the results of GL-480-ORG and a negative impact on PP-380-ORG.

Since the study was limited to the use of secondary data, generalization of these results is limited. Furthermore, these results are only applicable to Austria, due to recycling rates of packaging and costs of these products are only viable for this country. Depending on the country of marketing, the evaluation could change substantially. Furthermore, the difference of organic and conventional agriculture could not be captured in the calculation of LCA and VA, which however was addressed by considering it as an additional criterion in the MCDA.

4. Conclusions

The main aim of this study was to combine environmental and economic assessments of food-packaging systems, including and putting the focus on indirect effects of food loss. Historically, most LCA studies of packaging did not consider FLW (Molina-Besch et al., 2018), predominantly due its quantification being challenging (Wohner et al., 2019a). In this study, FLW was quantified by testing the emptiability of products, which was then integrated into the LCA and VA calculations of the examined products. As a result, environmental impacts increased, and more surprisingly, also the value added to the economy, which is, however, inherent in the respective method (Wood and Hertwich, 2013).

A further limitation is the exclusion of criteria of taste or quality. A point could be made that PP-380-ORG is the product with the highest tomato content and thus the one with the highest quality. However, this is highly subjective and would have to be the subject of sensory testing which was outwith the scope of this study.

We conclude and agree with authors of similar previous studies that TOPSIS assists in overcoming the limitations inherent in LCA

Table 3
Decision matrix of TOPSIS for case study. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.
Abbreviations for criteria represent, beneficial (B) or non-beneficial (NB): CC (climate change), FRD (resource use, fossils), WU (water use), FEU (Eutrophication, freshwater), AC (acidification), PM (Particulate matter), and VA (Value Added).

		Type of criterion	Unit	PP-450-CNV	PP-380-ORG	PP-550-ORG	GL-480-ORG
LCA	CC	NB	kg CO_{2eq}/FU	5.97E+00	9.16E+00	5.66E+00	6.54E+00
	FRD	NB	MJ/FU	9.40E+01	1.37E+02	8.62E+01	9.65E+01
	WU	NB	m^3_{eq}/FU	1.23E+01	2.15E+01	1.28E+01	1.29E+01
	FEU	NB	kg P_{eq}/FU	1.40E-03	2.11E-03	1.26E-03	1.58E-03
	AC	NB	mol H^+_{eq}/FU	3.90E-02	6.06E-02	3.54E-02	4.95E-02
	PM	NB	disease incidence/FU	3.02E-07	4.72E-07	2.82E-07	4.51E-07
Organic agriculture		B	yes (1) / no (0)	0	1	1	1
Value added		B	€/FU	13.02	17.83	11.67	9.85

Table 4
Weights of criteria, calculated using equal weighting ('EQUAL'), CRITIC and entropy. Abbreviations for criteria represent: CC (climate change), FRD (resource use, fossils), WU (water use), FEU (eutrophication, freshwater), AC (acidification), PM (particulate matter), and VA (value added).

Category	Criteria	Equal	Critic	Entropy
Life cycle assessment	CC	12.5%	6.8%	14.4%
	FOSSILS	12.5%	7.5%	13.9%
	WATER	12.5%	8.4%	17.3%
	FW_EUTROPH	12.5%	6.8%	14.3%
	FW_ACID	12.5%	8.0%	14.2%
	RESP	12.5%	15.2%	13.3%
Organic agriculture	Yes/no	12.5%	32.2%	7.5%
Economic assessment	VA	12.5%	15.2%	5.1%

studies (Maxim, 2014; Niero and Kalbar, 2019), such as only considering environmental performance, while excluding assessments of other sustainability dimensions (Zimek et al., 2019) or compliance with environmental regulations (Levy, 2017). The proposed sustainability assessment of food-packaging systems can solve multi-dimensional issues, particularly of conflicting sustainability goals. TOPSIS provides a single score and therefore an easy to understand indication of the best possible solution. However, it is not without its limitations. TOPSIS does not provide a 'final word' since the selection of criteria and weights strongly influence the results, again shown in this study. Furthermore, sustainability may be considered as a social construct and, arguably, weighting sets should then only be determined subjectively (Mollayosefi et al., 2019). While this may be a benefit due to it being highly adaptable to the preferences of one decision maker, it is then challenging to compare the results of one such study to those of others (Maxim, 2014). A natural progression of this work would be to apply this method to an increasing number of different food-packaging systems. Furthermore, future studies could incorporate social life cycle assessments to depict all three pillars of sustainability. Additionally, the economic assessment could be enhanced by developing environmental LCC methods which cover a more extensive scope of economic sustainability. Finally, while admittedly challenging, a greater focus on quantifying FLW besides emptiability and the integration into such assessments would produce a better and broader insight into the sustainability of food-packaging systems.

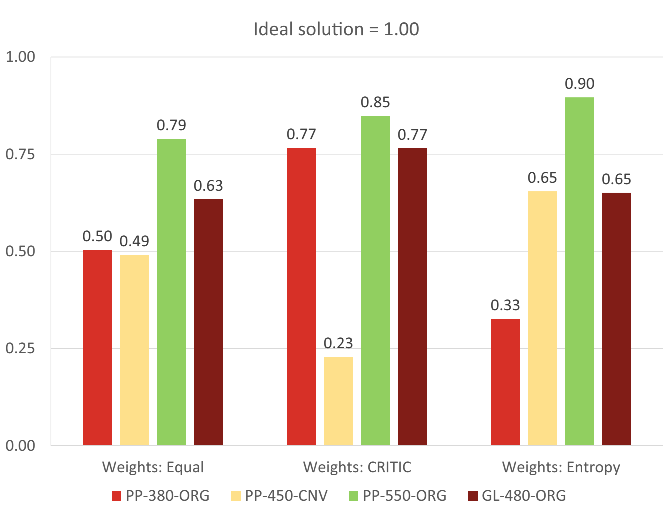

Fig. 5. Relative closeness values of products. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

CRediT authorship contribution statement

Bernhard Wohner: Conceptualization, Formal analysis, Validation, Writing - original draft, Writing - review & editing, Visualization. **Viktoria Helene Gabriel:**Conceptualization, Writing - review & editing.**Barbara Krenn:**Conceptualization, Formal analysis.**Victoria Krauter:**Conceptualization, Validation, Writing - review & editing, Supervision.**Manfred Tacker:**Conceptualization, Validation, Resources, Writing - review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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