Research Article

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Decision on single-use and reusable food packaging: searching for the optimal solution using a fuzzy mathematical approach

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Abstract

BACKGROUND: In modern food supply chains it is becoming increasingly important for companies to have sustainable product packaging systems. Deciding the protection, marketing, and logistical function of packaging, at optimal cost, is a very complex matter for professionals. The decision is usually between disposable (single-use) and reusable (returnable) packaging solutions and their special characteristics. In practice, the focus of this decision is based on historical experience and traditions, taking a cost-based and/or a criteria-based approach. This considers a wide range of cost factors. Packaging cost is an important factor, but not the only one, in determining the optimal solution.

RESULTS: This study presents a three-dimensional fuzzy signature model with a fuzzy method that can be applied to the packaging decision problem to investigate the interconnections among factors that affect the final results, beyond simple binary logic. Two types of food packaging, beverage glass and polyethylene terephthalate (PET) bottles, were chosen to validate the usability of the model.

CONCLUSION: Fuzzy signatures can model the subjectivity of human definitions and criteria using the knowledge of professionals – human knowledge, which is experienced under real conditions and is used in practice in the food-packaging decision process. Food-packaging decision components and the final decision can be determined by fuzzy algorithms using membership functions on aggregation and weighted values.

Supporting information may be found in the online version of this article.

Keywords: packaging; circulability; sustainability; reusable; disposable

INTRODUCTION

Packaging is a necessary part of any supply chain.[1] To optimize packaging, those who are involved in the decision-making process first have to decide between disposable and reusable systems, or a combination of the two. The primary function of packaging in logistics is to help processes such as handling and transportation at a reasonable cost.[2] Obviously, cost cannot be the only factor in this analysis. It is not enough to define the necessary protection or the cost of materials and the investment required. Many other factors have to be considered, such as cleaning, storage, maintenance, administration, and CO_2 emissions. These factors have to be addressed in a comprehensive analysis. A very significant part of global primary energy use and CO_2 emissions is related to the production of materials,[3] and this is also true for packaging production. Novel technological approaches or the use of natural substances for packaging can be sustainable solutions,[4] but improved management of packaging can also result in a reduction in damage to the environment. One of the most promising improvements can be the substitution of disposable packaging with reusable packaging. Improving the efficiency of packaging is becoming an important goal for companies that are concerned about both sustainability and economically efficient production.[5]

Nowadays, when considering the issue of packaging in food supply chains, circulability and sustainability are key concerns.[6] Increasing amounts of 'big data' from food supply chains are available, which give a better understanding of the food packaging factors that can lead to more circulable and sustainable alternatives.[7]

In the total supply chain, an optimal balance has to be found between necessary production and reuse of packaging; this means that specialists are faced with a very complex and varying decision process. In the last 20 years, research has recommended decision models focusing on relative cost-based analysis,[8] life

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cycle assessment (LCA) analysis,[9] carbon emission analysis,[10] or a combination of these with multi-criteria decision analysis (MCDA).[11,12] The subjects of these models have ranged widely in terms of packaging, from the automotive sector to the food and agriculture industry. There are studies that considered the cost structure of packaging systems[13] and investigated consumer behavior using game theory.[14]

The aim of this short article is to present a novel method for modeling the decision process related to food-packaging solutions. The reason for using fuzzy mathematics was to find a method to solve food-packaging choice problems that involve many uncertainties and for which simple binary logic (cost-based, carbon footprint, or LCA analysis) would be inappropriate. Fuzzy analysis is also used in multiple disciplines, including decision-making problems, planning, and production. The main focus is on those factors that affect food-packaging decisions directly, excluding the direct comparison of purchase prices. Two studies have already been conducted on this topic, investigating returnable and single-use automotive packaging and packaging for dangerous goods using this fuzzy method.[15,16] In these papers fuzzy theory appeared only once in the context of packaging technology and this research used a fuzzy comprehensive evaluation analysis for the green rationality of paper and biomass packaging materials.[17] Fuzzy techniques in agriculture are a relatively new research direction with topics such as a fuzzy decision support systems for nitrogen fertilization,[18] a fuzzy controller to reduce tomato cracking in greenhouses,[19] a fuzzy logic-based disease diagnosis system for crops,[20] and fuzzy analysis of edible bird-nest processing.[21]

With regard to the protective function of packaging, the decision-making process is a choice between single-use (disposable) packaging and reusable packaging. The first is a suitable solution for single-use only, while reusable packaging can be sent back to the supplier for refilling. This process will be repeated; creating a cycle that builds up a closed or open-loop system.[13] There are several factors that affect the packaging that can be used in a given situation. On the product side, these can be the special properties of the product, including, for example, its sensitivity and its relationship with the packaging material. From the corporate economics point of view there are additional factors, such as manufacturing, storage, transportation, managing, and cleaning costs. However, for most variables no clear binary logic can be identified.In practice, the return of packaging usually depends on transportation or collecting distance but this decision should be based on the complexity of the supply chain characteristics. When considering transport, the relationship between subfactors must be taken into account, and their effects on other factors as well.

This method is a novel technique to help decision makers to support decisions regarding whether a disposable (single-use) or returnable packaging system should be used. The aim of this method is not to produce a holistic or comprehensive (cost-based) comparison but instead to investigate factors that influence the decision process and provide an approach that goes beyond traditional binary logic. The fuzzy model presented here, based on packaging characteristics offered by packaging experts, has provided an effective support mechanism that has been applied in real life.

MATERIALS AND METHODS

Preliminary (fuzzy signatures)

Fuzzy theory uses sets. In mathematics fuzzy sets are elements of objects that have grades of membership, where a set is characterized by a membership function that assigns a grade of membership ranging between 0 and 1 to each object:[22]

$$\mu_A(x) : x \longrightarrow [0,1]; \forall x \in X, \quad (1)$$

where $\mu_A(x)$ is the membership function of set A.

In traditional set theory, elements can either belong to a set or not. So, their value can be 0 or 1. However fuzzy theory allows us to describe elements between these values in the interval [0,1] with a membership value. In this way an element can have an intermediate value when, for instance, there are domains in which information is incomplete or not totally perfect.

A fuzzy set is characterized by a membership function.[23] The most commonly used fuzzy numbers are triangular and trapezoidal fuzzy numbers; in this study they are both used. Figure 1 shows membership function[20] descriptions of a fuzzy number where the value is ‘approximate 1’. It is clearly visible that the triangular shape characterizes the number in which the degree of belonging to the fuzzy set equals 1 (only at $x = 1$), and how the distance increases when the membership function of x decreases from 1; the fuzzy set is decreased. However, in the trapezoidal membership case the fuzzy set is not only equal to

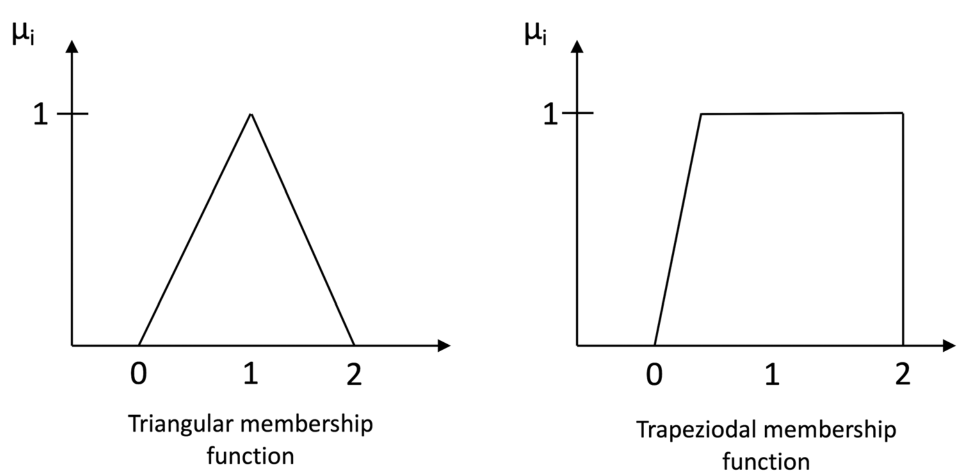

Figure 1. Fuzzy membership function samples (triangular, trapezoidal).

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1 when $x = 1$. As we can see, the shape of the membership function determines the levels of uncertainty on a given factor.

Kóczy *et al.*, in 1999, introduced fuzzy signatures, which are a generalized form of vector-valued fuzzy sets. These can describe objects with a set of qualitative measures. A fuzzy signature is defined as a special multidimensional fuzzy data structure. Dimensions of structure are interconnected in the sense that they form a subgroup of variables that together define a higher level characteristic. This can be expressed as follows:[24]

$$A_S : x \to [a_i]_{i=1}^{k} = \begin{cases} [0,1] \\ [a_{ij}]_{j=1}^{k_i} \end{cases}, a_{ij} = \begin{cases} [0,1] \\ [a_{ij}]_{j=1}^{k_i} \end{cases}, \forall x \in X \quad (2)$$

Fuzzy signatures, with their hierarchical symbolic representations, make it easier to structure the data into vectors of fuzzy values. Furthermore, with the help of signatures, the model of the task can be organized into a hierarchical system,[25] which is very similar to the way human experts think.[23] This can be seen in Fig. 2.

Aggregation method

When specialists make decisions, the fuzzy signatures can change continuously from observation to observation, which can modify the whole operation in hierarchical system from level to level. So, the aggregation node will result in a single fuzzy value from a set of other fuzzy values; a parent node can be obtained by aggregating the values of its sub-tree. Generally, the operators are the maximum, minimum, or the arithmetic mean.

For one packaging solution decision five packaging specialists' opinions were used as the basis and the arithmetic weighted average (AWA) was aggregated. The AWA can be expressed as follows: if n values (the internal node) has n children nodes (which have their own assigned membership functions or are outputs of other aggregations – here, the membership degrees are denoted by the letters μ) with predefined values for weights (denoted by w_i), then subsequently the output of the aggregation can be calculated:

$$\overline{\mu} = \frac{\sum_{i=1}^{n} w_i \mu_i}{\sum_{i=1}^{n} w_i}, \quad (3)$$

where $\mu_1, \mu_2, \ldots, \mu_n$ is the element of signature, and $w_1, w_2, \ldots, w_n$ is the non-negative weight.

Fuzzy modeling with the application of signatures

Some principal steps are required to allow decision making on the basis of fuzzy logic. Fuzzy inference systems allow decision making on the basis of fuzzy logic inferences. They operate using the following steps[26]:

(1) The decomposed input factors can be fuzzified. This is the process that converts a crisp input value to a fuzzy value. It is performed by using information in the knowledge base. (These are the weights and aggregation nodes.)
(2) Fuzzy inferences are applied. The signature tree is customized by the membership functions. (This is called the signature levels.)
(3) The outputs are computed by obtaining a single number. This basically means that a defuzzification process is used to transfer fuzzy inference results into a crisp output.

METHODS (FOOD-PACKAGING DECISION)

In this section, a three-dimensional fuzzy signature is presented with fuzzy rules that can be applied to the packaging decision problem. In real industrial practice three sets can be defined, which are interconnected in the sense that the sub-tree of

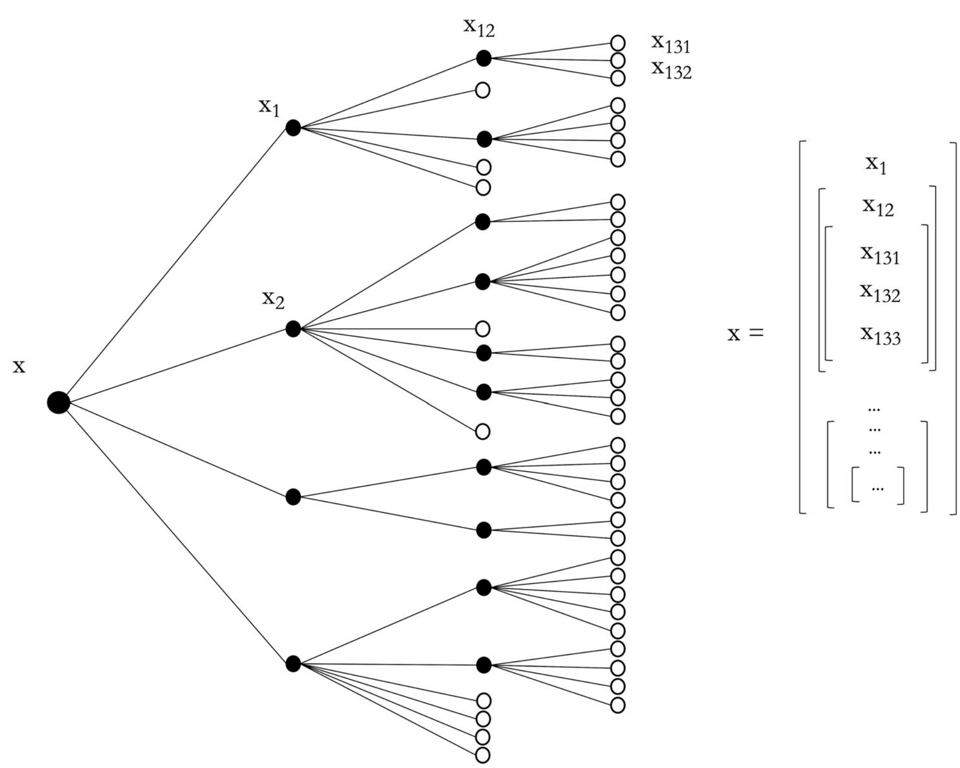

Figure 2. Fuzzy signatures in vector form and tree structure.

variables determines a given characteristic at a higher level. This can be seen in Fig. 3. The basis of this selection is that the components inside are interrelated in the sense that a given sub-group of variables can determine another feature at a higher level. The features of these signatures will be explained in detail later.

As was mentioned previously, obtaining proper aggregation operators is a fundamental issue. This fuzzy method uses five packaging experts' opinions as a basis for this, and then their joint opinion determines the weights (w_i) for both leaves (with membership functions, μ_i) and intermediate nodes (parent with aggregations, a_i).

The relation among the three signatures is determined by the following rules:

Rule S_1: ***if*** *$\mu S_1 \geq 0.5$* ***then*** *check S_2 else disposable*
S_2: ***if*** *$\mu S_1 \geq 0.5$* ***and*** *$\mu S_2 \geq 0.5$* ***then*** *check S_3* ***else*** *disposable*
S_3: ***if*** *$\mu S_1 \geq 0.5$* ***and*** *$\mu S_2 \geq 0.5$* ***and*** *$\mu S_3 \geq 0.5$* ***then*** *returnable* ***else*** *disposable*

where S_i is the fuzzy signature level. The rules stated above can be extended with further fuzzy signatures. Adding, deleting or replacing some sub-trees or simple leaves in the structure could be necessary depending on the packaging observed.

For each leaf and intermediate node, the values (μ_i) have to be in the interval [0,1]. The membership function value is derived as follows: first the shape of membership function is determined then any input variable given is the degree of belonging to the fuzzy value. A numerical example is shown in Appendix S1. The exact value is defined based on its meaning and role. On a given

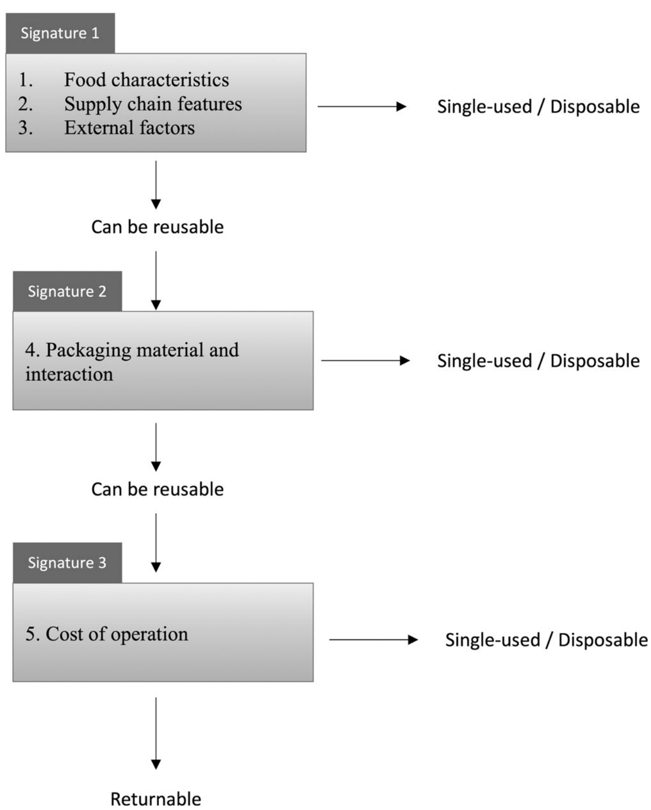

Figure 3. Hierarchical fuzzy signature model for food-packaging decision process.

level the connection among the leaves (individual descendants) is determined by aggregations. In the end, if the final value created by the aggregation in the main root (a_0) is closer to 0, then the packaging to use should be disposable (single-use); if the result of a_0 is closer to 1, the packaging should be returnable Fig. 4.

Aggregation operators

The panel discussion with the packaging experts concluded that the aggregations were to be weighted with the arithmetic average.

Main aspects and its weights for food packaging

The following sections describe the parent and child nodes. As a result of the packaging experts' panel discussion a linear scale was used to determine the weights for both the parent and child nodes. The numerical results of the panel's opinion can be found in Appendix S2. Steps for the determination of weights were as follows: (i) a possible list of aspects was created; (ii) the discussion with the packaging experts was held; and (iii) an agreement was reached among the experts about the weights. Of course, there are several methods to define the weights more exactly but this was not the focus of this study. Furthermore, the weights can be rebuilt repeatedly. Table 1 contains the weights of the various roots for the sub-trees. The position (index) of the given aspect (as a leaf or aggregation) in the entire fuzzy signature model is represented by ID.

Food product characteristics

The specification of food product features is essential for defining and choosing the proper packaging for food products. Table 2 contains the weights for fuzzy aggregation of food product characteristics. These specifications include technical details such as product manufacturing, geometrical sizes, and the sensitivity to various circumstances – this being one of the most important issues.

Supply-chain characteristics

Table 3 presents the weights for the logistical and supply-chain components. There are three components of particular importance: transportation distance, volume/capacity ratio of goods delivered at the same time in the transportation sub-tree, and sensitivity of refrigerated goods during distribution and storage. Furthermore, the sensitivity of fragile products to shock or dropping can also play an important role when deciding on returnable packaging.

External factors

Naturally, there are factors that influence the decision indirectly, such as regulations, legal aspects and external conditions. These can be found in Table 4. They are almost all packaging-related factors, such as energy consumed in packaging production, CO_2 emissions of inverse logistics, and vehicle utilization.

Packaging solution material and devices

After the first signature, when the model gives a possible solution for reusable packaging, the packaging design and material characteristics of packaging used should be considered. These aspects can be found in Table 5, and they include the available packaging material, recyclability, weight, reusability, or the possible number of uses (referred to as technical suitability).

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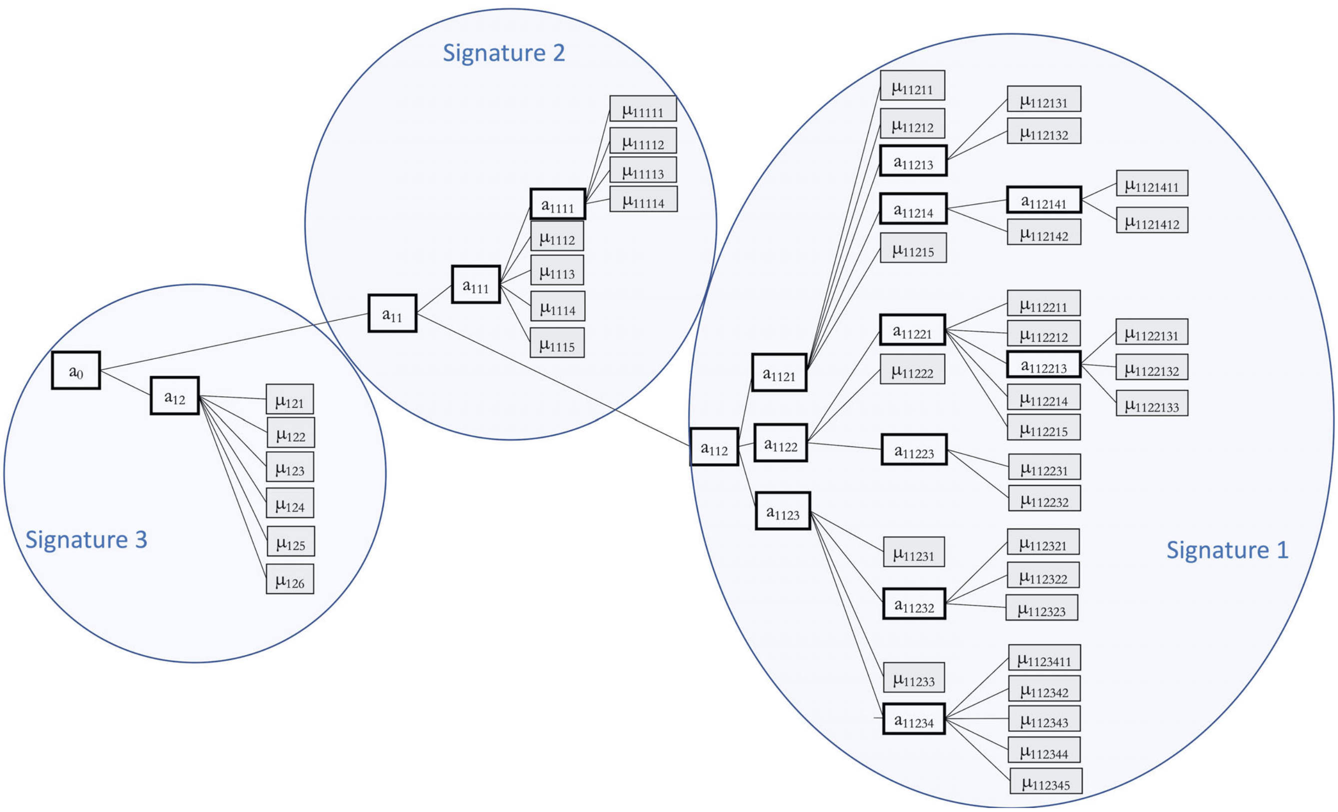

Figure 4. Tree-structure of fuzzy signatures for this study.

Table 1. Weights of the aggregation operators in the food-packaging model

ID (a_i, μ_i)	Feature	Weight (w_i)
0	S_3 root	–
12	Cost of operation	7
11	S_2 root	4
111	Packaging material and interaction	10
112	S_1 root	4
1121	Food product characteristics	9
1122	Supply chain	6
1123	External factors	2

Table 2. Weights for food product characteristics and their respective sub-trees

ID (a_i, μ_i)	Feature	Weight (w_i)
11211	Turnover	7
11212	Shelf life	9
11213	Geometrical characteristic	5
112131	Shape	4
112132	Size/weight	2
11214	Sensitivity	9
112141	Physical	6
1121411	Mechanical	5
1121412	Climate	7
112142	Biological	8
11215	Value	4

Cost of operation

In industrial practice, operational cost is generally most important. The reason for putting this in the third signature is that the difference in cost structure, both for single-trip and reusable food packaging, is fundamental. Those cost components that can occur in a reusable system, for example the cleaning, maintenance or administration tasks, but cannot occur in disposable packaging system. Table 6 contains the weights for the third fuzzy signature. Here, according to the experts' opinion, all these features have similar importance.

At this point in the study the shape of the membership functions has to be determined. Theoretically, there are many different membership functions;[18] however, in many practical applications, triangular and trapezoidal membership functions are the most efficient ones, and the simplest linear membership functions work very well too.[27] So, this study also applies these simple membership functions as the variants of the triangular or trapezoidal membership functions, otherwise this linear intuition coincides with the linearity of the input values used for this study. For more detail on this linear behavior, Appendix S1 shows membership functions for transportation factors with numerical data, and Appendix S3 contains the shape of membership functions for each input variable.

RESULTS AND DISCUSSION

For this study a simple program code (in C++) was written with a text file to determine the AWA and to calculate the results of the root between 0 and 1 for the possible food-packaging

Table 3. Weights for supply-chain components

ID (a_i, μ_i)	Feature	Weight (w_i)
11221	Transportation	9
112211	Distance	8
112212	Volume/capacity	7
112213	Distribution circumstances	5
1122131	Temperature	7
1122132	Vibration	1
1122133	Humidity	2
1122134	Shock/drop	5
112214	Infrastructure	2
112215	Modality	1
11222	Logistics IT	5
11223	Material handling	2
112231	Transshipment	5
112232	FTL/LTL	4

Table 4. Weights for external factors components

ID (a_i, μ_i)	Feature	Weight (w_i)
11231	Cooperation	8
11232	Regulations	5
112321	Environmental	2
112322	Human health	6
112323	Related standards	2
11233	Legal issues	4
11234	Environmental effects	3
112341	Production related	10
112342	Raw material	10
112343	Energy consumption	8
112344	CO_2 emission	8
112345	Vehicle utilization	4

Table 5. Weights for food-packaging material components

ID (a_i, μ_i)	Feature	Weight (w_i)
1111	Used material	9
11111	Robustness	5
11112	Material availability	5
11113	Material recyclability	7
11114	Tare weight	2
1112	Packaging fill rate	8
1113	Reusability	7
1114	Possible number of uses	7
1115	Collapsibility	7

alternatives. This can also be calculated manually. As indicated in the method section, if the result is close to 0 (say, less than 0.5), it means the packaging should be single use (disposable). When it is over 0.5 or close to 1, it should be reusable.

Case study results

A food packaging case study illustrates the decision-making calculation. This case study used glass and polyethylene terephthalate (PET) bottles for beverages. The components of the glass packaging consisted of a 0.25 L glass bottle (1 pc, 245 g), an etiquette label (1 pc, 0.03 g), and a metal cap (2 g). The geometrical size of the unit was 60.3 × 196 mm. The result of the calculation concerning this glass bottle was then compared to the calculation of a well-known 0.5 L PET bottle, which was partly performed in another research[16] led by the author (in that study the variables and their weights do not overlap perfectly with this study). Its components consisted of a PET bottle body (10.3 g), a high-density polyethylene (HDPE) cap (5.10 g), and a polyethylene (PE) etiquette label (0.01 g), with a total weight of 0.01541 kg (15.41 g).

For the glass bottle the calculation first passed the first signature with a value of $a_{112} = 0.569260$, then passed the second signature with a value of $a_{11} = 0.677980$, and the final third signature was $a_0 = 0.702535 > 0.5$, which means that the beverage glass bottle should be reusable. In the PET bottle study, the calculation stopped at the second signature with a value of $a_{11} = 0.489458 < 0.5$, after it passed the first signature with a root result of $0.523090 > 0.5$. This meant that the PET bottle should be disposable, as this kind of bottle is widely used in industrial practice.

Table 6. Weights for components of operational cost aspects

ID (a_i, μ_i)	Feature	Weight (w_i)
121	Packaging material	5
122	Disposal	5
123	Capital asset	5
124	Cleaning, maintenance	5
125	Storage	5
126	Administration	5

DISCUSSION

The study provided a food-packaging case study with two possible packaging solutions. Despite the relative low calculation value of glass packaging ($a_0 = 0.702535$) in regard to many aspects, such as weight/capacity ratio, shipping cost, manufacturing cost, energy consumption, or fragility, the fuzzy model identifies it as reusable packaging, which is still the industrial practice. Nevertheless, it has been significantly overshadowed by PET bottles in recent years. The value of 0.702535 confirmed the industrial practice that the packaging has to be reusable. At the same time, there is a need to investigate variables that can improve the final result, such as the factors affecting reverse logistics or accurate knowledge of the return rate of glass packaging.

In the case of PET bottles, it was surprising that they almost reached the third signature. Although refillable PET bottles exist and in the past were in use for a long time, the model still considers them to be single-use packaging. The value of 0.489458 at the second signature stopped the calculation; thus, it did not reach the investigation section of cost aspects. In this case, it would be worthwhile examining those conditions that would allow for further investigation into the cost of operation signature level.

Readers have to take into account characteristics of components that can be very complex, so an unwanted simplification can pose a risk to the complex decision process; practically it is almost impossible to estimate the full effect of a combination of factors. On the other hand, some factors are considered in an integrated way.

Some interrelations could not be perfectly handled by the model, such as the interrelation of logistics efficiency between food packaging and supply-chain characteristics. For instance, both of the two packaging solutions can be operated by automatic equipment to different degrees, and the reverse logistics aspects of the two solutions can be varied due to the potential for volume reduction or consumer return rate. Furthermore, the signature, which involves and is responsible for the cost aspect of packaging, itself depends on the cost of packaging and has a significant impact on the entire supply chain (i.e., enabling transport and logistics efficiency), or has the capability to minimize packaging waste at the end of its lifetime. Thus, these factors are considered in an integrated manner, as it is the sum of these factors that determines the total cost of packaging in Signature 3.

At the same time the fuzzy model needs the subjectivity of human definitions and experts' knowledge about the weights at aggregation nodes criteria to model the interrelation of variables, in opposite to other methods, such as cost-based, carbon footprint or LCA. In the context of single-use and reusable food packaging, a non-probabilistic type of mathematical model is required due to the 'loose' mathematical conditions involved. An approach that assumes the presence of simple additive (probabilistic) measures will lead to a distorted representation of the packaging problem.

CONCLUSION

The fuzzy signatures algorithm is based on decision components' characteristics offered by packaging experts. The fuzzy method uses the knowledge of professionals and human knowledge based on experience of real conditions and practice. Fuzzy signatures can model the subjectivity of human definitions and criteria. The fuzzy model presented in this study can be a novel method that can aid the decision-making process when comparing single-use (disposable) and reusable food packaging solutions, beyond the traditional cost-based methods.

Naturally, numerous case studies have to be conducted in the future to establish a general decision support tool for food-packaging solutions. Research is continuing to adjust the model, especially by separating traditional polymer and bio-based packaging, and modeling the environmental issues in more detail. In a subsequent paper these results will be presented after various packaging systems are evaluated using different kinds of biomaterial.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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