Chair of Waste Processing Technology and Waste Management

Master's Thesis

Recycling Potential of Multilayer Films

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Abstract

Recycling potential of multilayer films

This master thesis is part of the project Multilayer Detection and consists of three parts. Firstly, a material flow analysis (MFA) of a flexible plastic packaging recycling plant was conducted. The findings of the MFA are complemented by expert invterviews of the on-site personnel to display the current challenges, which operators of a plastic recycling plant for flexible waste plastic packaging have to face at present. Secondly, the input material of such kind of plants, the 2D fraction from a lightweight packaging sorting plant, was manually sorted with a special focus on multilayer films. Finally, considerations on a design concept for a sensor-based sorting unit was developed to allow future adjustment of recyclate quality, especially targeting at the detectability of multilayer films.

The result of the MFA and the expert interview identified the following areas as the main technical and waste management challenges posed to a flexible plastic packaging waste recycling company: (1) feedstock, (2) plant set-up and process technology, (3) personnel, (4) quality assessment, (5) by-products of the recycling process and the (6) secondary raw material market. Multilayer films pose a particular challenge. Due to their structure, the means to recycle them are very limited. Without technology to detect them, they can have a negative influence on the recycling of the valuable polyethylene monofilm fraction.

The hand sorting analysis of a non-representative 39.3 kg random sample of the Austrian yellow bag collection resulted in a sample of 10.4 kg, or n=842 objects, of two-dimensional flexible waste plastic packaging which have been assessed regarding packaging category and product category. Another subtotal of n=143 objects is examined by the means of FTIR-ATR to investigate whether or not multilayer films are present. It turned out that n=45 specimen are identified as multilayer films, which accounts for a share of 24 w-% in the flexible waste plastic packaging fraction and 6 w-% in the yellow bag collection. The packaging group in which multilayer films are most frequently found with share of 49 w-% is food packaging, of which they are most likely present in packaging of bakery products (16 %), meat (13 %) and dairy (9 %) followed by frozen food and convenience products (9 %). Assuming the ideal recycling potential is equal to the content of multilayer films in the Austrian yellow bag collection, the total ideal recycling potential of multilayer films in the separately collected plastic packaging waste is estimated to be 10,260 tons per year. Recycling these laminated films can ideally increase the Austrian recycling rate of plastic packaging waste by 3 w-% from 25.7 w-% to 28.7 w-% under the premise that specific recycling technologies for multilayer films are available. The use of new advanced NIR sorting technology beyond the detection of multilayer films can additionally uncover previously untapped resource potential of the two dimensional plastic packaging fraction by further separating it into recyclable clean monolayer streams. Therefore, assuming a recycling efficiency of 100 % and that no more plastic films have to be incinerated, the theoretical recycling rate raises by 14 w-% from 25.7 w-% to a hypothetical maximum of 39.7 w-%.

In order to adapt the presented experimental NIR sensor sorting stand two strong levers are identified to improve the spectral quality for the detection of multilayer film: signal intensity and signal density. It is therefore recommended to adjust the illumination intensity, install a diffuser hemisphere or panels next to the conveyor belt or the material chute, changing the NIR measurement mode to transflection, and a change of the chute material to aluminium. A corresponding experimental procedure for their investigation is proposed.

Kurzfassung

Recyclingpotential von Mehrschichtfolien

Diese Masterarbeit ist im Rahmen des Projekts Multilayer Detection entstanden und besteht aus drei Teilen. Zuerst wird eine Materialflussanalyse (MFA) einer typischen Recyclinganlage für Kunststoffleichtverpackungen durchgeführt. In Kombination mit Expertengesprächen mit den Mitarbeitern der Anlage aus allen Managementebenen werden die aktuellen Herausforderungen des Kunststoffrecyclings herausgearbeitet. Im zweiten Teil wird der Input einer solchen Anlage für Kunststoffleichtverpackungen mittels Handsortierung, mit besonderem Fokus auf den Verbleib und das ideale Recyclingpotential von Mehrschichtfolien, untersucht. Abschließend werden Überlegungen hinsichtlich der Entwicklung eines Designkonzepts für einen experimentellen Sortierstand ausgestattet mit einer Nahinfrarot (NIR) Hyperspektralkamera angestellt, um durch gezielte Verbesserung der Spektralgüte die Sortiertiefe von Kunststofffolien im Allgemeinen und die Detektierbarkeit von Mehrschichtfolien im Speziellen zu ermöglichen.

Auf Grundlage der MFA in Kombination mit den geführten Experteninterview sind folgende technische und abfallwirtschaftliche Herausforderungen aus den Bereichen (1) Inputmaterial, (2) Anlagenkonzept und Verfahrenstechnik, (3) Personal, (4) Qualitätskontrolle, (5) Nebenprodukte und der (6) Sekundärrohstoffmarkt identifiziert und diskutiert worden. Eine besondere Herausforderung stellen dabei Mehrschichtfolien dar. Diese können auf Grund ihres Aufbaus bis dato nicht bis kaum rezykliert werden, aber beeinflussen das Recycling der Polyethylen Monofolienfraktion negativ.

Die Handsortieranalyse einer nicht repräsentativen 39,3 kg umfassenden Stichprobe aus der österreichischen Leichtverpackungssammlung ("Gelber Sack") zeigt auf, in welchen Produktströmen Mehrschichtfolien tendenziell anfallen und dient als Grundlage für die Abschätzung ihres idealen Verwertungspotenzials. Insgesamt werden 10,4 kg, beziehungsweise n=842 Objekte, an zweidimensionalen flexiblen Kunststoffverpackungsabfällen nach Verpackungs- und Produktkategorien gesichtet und ausgewertet. Mittels FTIR-ATR Analyse wird eine kleinere Teilmenge dieser Objekte (n=143) untersucht ob sie Mehrschichtfolien sind. Es stellte sich heraus, dass n=45 Exemplare als Mehrschichtfolien identifiziert werden konnten, was einen Anteil von 24 m-% in der Fraktion der flexiblen Kunststoffverpackungen und einem Anteil von 6 m-% in den Leichtverpackungen ausmacht. Die Verpackungsgruppe, in der Mehrschichtfolien mit einem Anteil von 49 m-% am häufigsten zu finden sind, sind Lebensmittelverpackungen, dort kommen sie unter anderem am häufigsten als Verpackung von Backwaren (16 %), Fleisch (13 %) und Molkereiprodukten (9 %) vor, gefolgt von Tiefkühlkost und Fertigprodukten (9 %).

Unter der Annahme, dass das ideale Verwertungspotenzial dem Gehalt an Mehrschichtfolien in der österreichischen Gelben-Sack-Sammlung entspricht, wird das gesamte ideale Verwertungspotenzial von Mehrschichtfolien in den getrennt gesammelten Leichtverpackungsabfällen auf 10.260 Tonnen pro Jahr geschätzt. Durch das Recycling dieser Mehrschichtfolien kann die österreichische Recyclingquote für Kunststoffverpackungsabfälle im Idealfall um 3 m-% von 25,7 m-% auf 28,7 m-% gesteigert werden, vorausgesetzt, es stehen Recyclingtechnologien für Mehrschichtfolien zur Verfügung. Der Einsatz von fortschrittlicher NIR-Sortiertechnologie, kann neben der Ausschleusung von Mehrschichtfolien zusätzlich bisher ungenutztes Ressourcenpotenzial der zweidimensionalen Kunststoffverpackungsfraktion freigelegt werden. Sie ermöglicht es, die verbleibende zweidimensionale Kunststoffverpackungsfraktion noch weiter in recycelbare, saubere, einschichtige Kunststofffolienströme zu trennen. Geht man von einer Recyclingeffizienz von 100 % aus und davon, dass keine Kunststofffolien mehr verbrannt werden

müssen, erhöht sich die theoretische Recyclingrate um 14 m-% von 25,7 m-% auf ein hypothetisches Maximum von 39,7 m-%.
Um den vorgestellten experimentellen NIR-Sensor-Sortierstand anzupassen, werden zwei starke Hebel zur Verbesserung der spektralen Qualität für die Detektion von Mehrschichtfolien identifiziert: Signalintensität und Signaldichte. Es wird daher empfohlen, die Beleuchtungsintensität anzupassen, eine Diffusorhalbkugel oder -platten neben dem Förderband oder der Materialrutsche zu installieren, den NIR-Messmodus auf Transflexion zu ändern und das Material der Rutsche auf Aluminium umzustellen. Für die Untersuchung der vorgestellten Maßnahmen wird ein entsprechender experimenteller Versuchsplan vorgeschlagen.

Contents

1. Introduction

It is impossible to imagine today's society and economy without plastic and plastic packaging is in particular focus. Worldwide, 368 million tons of plastic were produced in 2019, of which 57.9 million tons in Europe (EU) (Europe 2020) They account for more than a third of all plastic products in Europe (Europe 2020) and are particularly conspicuous because of their short lifespan and ubiquitous distribution in the environment worldwide. According to Eurostat 2021, plastic packaging is accountable for 15.4 million tons or 177.4 kg of waste plastic packaging per citizen in 2019. Hence, the proliferation of plastic in all areas of life has become an increasingly visible issue and its impact on the environment is the subject of heated debate. Niaounakis 2020 tries to put the impact of flexible packaging and multilayer laminates in proportion to the European plastic demand, see Figure 1.1. In relation to the overall European plastic market of almost 48 million tonnes per year, the annual demand for flexible food packaging, which represents the largest fraction of flexible packaging, plays only a small role in the European plastic consumption. Multilayer films are supposed to have an even lesser share but do have nonetheless a substantial impact on the plastic recycling chain.

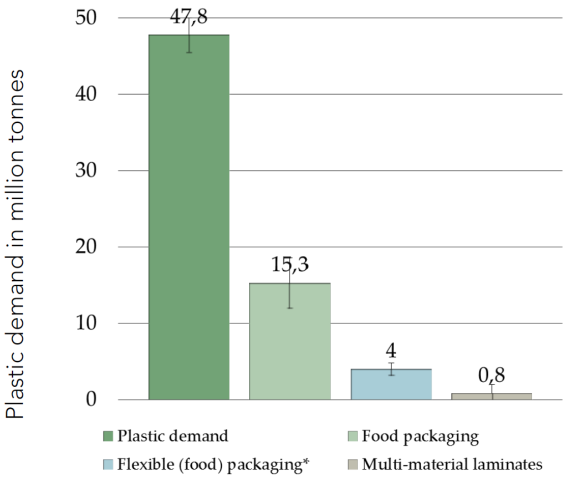


Figure 1.1.: Correlation of the European plastic demand and the share of multilayer films in flexible packaging (Niaounakis 2020, p. 19)

Table 1.1 gives an impression of the volume of the most common multilayer films in Europe 2016. First, the total quantity of the category is stated, followed by the largest representative for each.

1.1. Legal Framework

The European Green Deal and its Action Plan for the Circular Economy (European Union 2020), the basis for the European Plastics Strategy 2018 (European Commission 2018) and the Single Use Plastics Directive (European Union 2019) make reference to this issue of ubiquitous presence of plastic packaging. They promote awareness and reorientation of the European economy to break linear consumption and production patterns towards a more circular oriented society. In the area of plastics and plastic packaging, the main focus is on calling for extended producer responsibility and sustainable product policies. In total, 42.6 % of the post consumer plastic is incinerated for energy recovery, 24.9 % is disposed of in landfills and less than one third, 32.5 %, is subject to mechanical recycling. Even is Austria, most of the Austrian plastic packaging waste (74 w-%) serves as input for industrial incineration and 25.7 w-% are mechanically recycled (Van Eygen 2018, p. 111). Incentives for change are a rise of legally

Table 1.1.: Quantities of different multilayer films in Europe (Kaiser, Schmid, and Schlummer 2018, p. 5).

Type	Material	Mio. m² film	Share in m²-%
Plastic/Plastic without barrier	total	6565.6	37.1
	PA/polyolefin	2710.2	15.3
Plastic/Plastic with organic barrier	total	4499.9	25.4
	EVOH	4304.7	24.3
Plastic with metallized film	total	2996.1	16.9
	OPET/layer/polyolefin	1362.9	7.7
Plastic/Plastic with aluminium foil	total	1153.1	6.5
	PET/Al/plastic	829.1	4.7
Thermoformed packaging	total	2482.1	14.0
	PA/polyolefin	756.3	4.3
Total		17 696.9	100.0

binding recycling quotas to 50 % until 2025 and 55 % until 2030 and a demand for recycled material in new products, to name just a few.

1.2. Multilayer plastic packaging

However, plastic packaging is a high-tech product which despite its negative image can contribute positively to a sustainable society. In general, packaging has to meet multiple purposes. It aids in the distribution, protects goods from physical harm and environmental effects (contaminants, light, oxygen, odour, moisture), preserves freshness and correct weight, next to providing visually appealing information (Morris 2016, p. 14), leads to less food waste and reduces greenhouse gas emissions during distribution through an optimal product to packaging ratio (Nonclercq 2016; Denkstatt 2017). Various types of packaging come with good features to fulfill a range of these properties, however, there are limits. Metal cans do have excellent barrier properties, yet are heavy and opaque. Packaging made of glass makes the packaged product visible, but is prone to UV radiation and mechanical shock.
This drives the evolution of rigid packaging to a mix of flexible packaging material, typically made of polyethylene (PE, 44%), biaxially-oriented polypropylene (BOPP, 18%), paper (12%) or aluminium (10%). Smaller proportions are taken by cast polypropylene (PP), biaxially-oriented polyethylene therephthalate (BOPET), polyvinylchloride (PVC), ethylene vinyl alcohol (EVOH) and a variety of special materials for rare applications (Nonclercq 2016, p. 17).

1.2.1. Material Properties

These materials are either used on their own or in combination with each other due to their properties concerning structural integrity, barrier effects, sealing capability, the possibility to endure post-filling steps, adhesion, aesthetics, and costs (Dixon 2011). The multilayered multi-material structure is very beneficial in terms of packaging design, since every layer contributes with its own material specific advantages to the composite. To increase and combine the strength of different materials, up to nine layers are combined using lamination or co-extrusion. It is up to the converters to mix and match layers to adapt to custom applications. Table 1.2 compares properties of different base material for flexible packaging. In the list, more "+" indicate an increased usefulness in the described property and "0" symbolizes a total lack of it.

Table 1.2.: Comparison of typical flexible packaging material (Dixon 2011, p. 8). Abbreviations used: BOPET (biaxialyy oriented polyethylene therephthalate), EVA (ethylene-vinyl acetate), EVOH (ethylene-vinyl alcohol), LDPE (low density polyethylene), LLDPE (linear low density polyethylene), PA (polyamide), PP (polypropylene).

Material	Thickness	Tensile strength [1]	Light barrier	Heat sealing	Heat resistance	Relative cost [2]
LDPE [3]	30-70 µm	+	0	++++	+	+++
Paper	40-70 g/m²	+++	+	0	++++	++
Aluminium	6.3-12 µm	+	++++	0	++++	+++
Cast PP	40-70 µm	++	0	++++	+	++++
BOPET	12-19 µm	+++	0	0	+++	++
PP film	15-30 µm	+++	0	0	++	+
EVOH	3-10 µm	0 [4]	0	0	+	+++
PA	12-20 µm	++++	0	0	+++	++++

[1] Note that the strength is compared at the thickness indicated.
[2] The relative cost is compared for the thinnest grade mentioned.
[3] LDPE includes LDPE, LLDPE and copolymers e.g. EVA
[4] EVOH is not used on its own. Must be supported by other layer.

Structural Integrity Structural integrity ensures durability during processing, distribution and use. It is a function of tensile strength, yield strength, elongation at break, material E-modulus, impact strength and puncture resistance. Those properties directly correlate to the necessary film thickness and stiffness of the material in use. Materials providing proper stiffness are paper, oriented polypropylene (OPP) and oriented polyethylene terephthalat (OPET). It can be beneficial to put stiffer material on the inner or outer layers of the composite to establish sufficient resistance against torsion if needed. Another factor can be temperature. Especially high or low temperatures may melt or distort the polymer, which consequently leads to poor performance (Morris 2016, p. 69). Yet it may be necessary to endure those temperatures to enable certain post-filling steps such as retort, sterilization or blast freezing. If a material can not withstand those processes it is not a suitable choice (Morris 2016, p. 18).

Barrier effects Barrier layers are used to protect goods from contaminants and environmental effects. A frequent use case is to prevent food from spoilage. The four most common barriers in use are to protect the good from oxygen, carbon dioxide, moisture and light. Other substances in need of a barrier are grease or any kind of oil. Which barrier material is used is very much dependant on the packed product and the required shelf life (Morris 2016, p. 69). A subset of flexible packaging material is compared in Figure 1.2 by its permeability to water vapour and oxygen. Steel, aluminium and glass, of course provide excellent barrier properties. However, they are mostly heavy and rigid e.g. bottles, cans. Permeation is typically inversely proportional to thickness. Concerning flexible packaging, lower permeation can be achieved by increased gauge, by using suitable material, or by increasing the number of layers. Incorporating a thin and therefore flexible layer of Aluminium (Al) as barrier in the middle of two enduring polymer layers can prevent the Al layer from breaking, ensure good barrier properties with little more thickness, and maintain flexibility (Morris 2016, p. 15). Other materials providing a cost-effective moisture barrier are high density polyethylene (HDPE) and OPP. When an oxygen barrier is needed one might look for EVOH, polyvinyl alcohol (PVOH), polyvinylidene chloride (PVDC), oriented polyamide (OPA) or OPET. A light barrier is established by adding opacifiers such as titaniuim dioxide, metallization of a layer or by adding an aluminium foil. Typical oil resistant materials are of a polar nature or have high crystallinity, that is why e.g. HDPE is superior to low density polyethylene (LDPE). In this regard, polyamide (PA), PET and PVDC are a good choice for this application (Morris 2016, p. 70).

Sealing The sealing layer is the innermost layer of a multilayer composite. It provides hermetic sealing and protects the inside from the surrounding environment. The most common

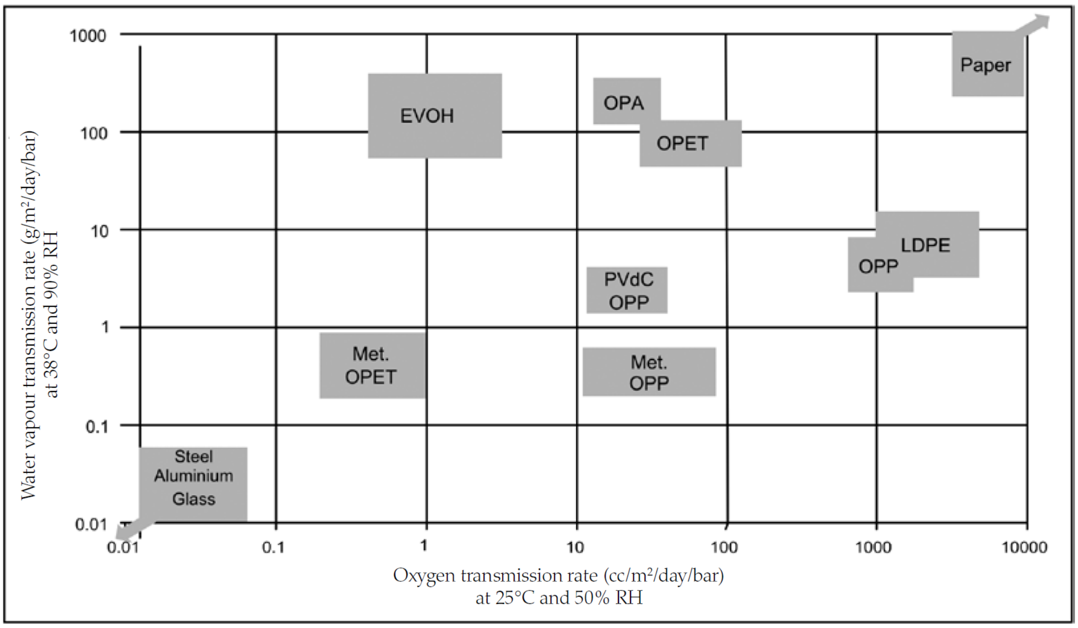


Figure 1.2.: Permeabilities to water vapour (y-axis) and oxygen (x-axis) of typical flexible packaging material (Dixon 2011, p. 7).

technique is thermally activated sealing. That is why a low melting point is a typical characteristic of a sealing material, since it ensures a low sealing initiative temperature. Additionally, heat sealing performance is in direct correlation with packaging line speed. The lower the melting point, the faster the sealing process is completed. Hence, typical material in use is a fast melting PE co-polymer like ethylene-vinyl acetat (EVA). Also common are LDPE, linear low density polyethylene (LLDPE) and ionomers. Other properties, which might need consideration, are the abilities to seal through greasy, oily, powdery substances or provide clarity, puncture resistance and stiffness (Morris 2016, p. 70). This is why PA is often used in packaging concerning meat and cuts.

Adhesion Given the different material of layers, most of them do not bond. Specific tie material helps to provide adhesion between layers, that ties them together. This bond can be mechanical and/or chemical. There exist two kinds of adhesives depending on the type of process. Using lamination, liquids like water or solvents are used. In co-extrusion or extrusion coating, molten polymer adhesives are applied to glue the layers to a consistent entity. Typical base resins, which act as adhesives are different grades of PE, acrylate copolymers and acid copolymers like EVA (Morris 2016; Wagner 2016).

Aesthetics Next to structural integrity, barrier performance and sealing, aesthetics plays a non-neglectable role. If the packed good is a consumer good, the packaging has to appeal to the consumer. The product might need to be visible through clear and transparent film or have a pleasant touch and feel. Then EVOH or PVDC might be favored over opaque layer material. colourful and bright printing can catch the attention of a potential customer, provide necessary information and still resist possible maltreatment along the distribution chain. Thus, the film must be printable, stable and enduring like OPET (Morris 2016, p. 70). Whether to print directly on the outer layer, or adhere to reverse printing, where the motive is printed in reverse on the inner layer of a protective film, is up to the customer.

Costs Of course, all of these properties come with a certain price. It depends on the material, the processing and the number of layers. In general, monolayers are cheaper than multilayers and metallized films are always more expensive than the non-metallized ones. Referring to Table 1.2, layers of PP and paper are most cost-effective and the use of LDPE, aluminium or OPET is always less costly than cast PP or PA. Therefore, it has to be considered in advance which needs the packaging has to fulfill and to what extent.

1.2.2. Multilayer Structure

Multilayer films can be characterized by their structure which is a build up of a variable number of stacked layers. The most simple multilayer is made of two distinct layers but more likely is a combination of three or five layers (Morris 2016, p. 10). More complex designs range from triple up to nine layers, providing even more functionality. However, they do not differ much in their structure, because the composition is always subject to the same rules.
The innermost layer provides (1) sealing. The middle layers are one or multiple (2) barrier layers to protect from oxygen, carbon dioxide, light or moisture glued together by (3) tie-layers that enable adhesion and protect from de-lamination. Finally, the outermost layer is a (4) structural layer responsible for resistance against rupture or punctuation. Several materials and their different roles in a multilayer composite are shown in Table 1.3. The German GVM 2016 defines 5 types of multilayer films. According to them, film can be classified either as monofilm (conventional plastic), flexible plastic/plastic composites without a barrier layer (PA/polyolefins, PET/polyolefins, PP/polyolefins, other plastic/plastic), plastic/plastic composites with organic barrier layer (plastic/EVOH/plastic, plastic/other organic barrier/plastic), composites of metallized film with coatings based on AlO_x or SiO_x (PET/layer/polyolefins, PP/layer/polyolefins, PA/layer/polyolefins), plastic/plastic composites with aluminium foil (polyolefins/aluminium/plastic, PET/aluminium/plastic, other plastic/aluminium/plastic) and thermoformed plastic. Further information on the characteristic structure of multilayer packaging broken down to specific product groups can be found at Morris 2016.
The structure of typical multilayer packaging is given by explaining the composition of two common product groups in the subsequent section: Bakery packaging and meat packaging.

Bakery Products Most important for bakery products is to keep them crisp, yet prevent them from getting dry. Therefore, a moisture barrier is integrated in the packaging. Polymers used to do so are LDPE, LLDPE, HDPE or PP. If sealing or good optics are necessary, EVA polymers are applied on the inner layer. A typical application is a bread bag. Sometimes small holes are poked into the film to preserve freshness by letting the product breath (Morris 2016, p. 700).

Meat Products The packaging of meat is a high tech designer product. It has to fulfill a wide range of characteristics. The product inside the package has to be kept fresh, needs to be seen, prevent freezer burn, help reduce purge loss when packed under atmosphere, extend shelf life, might need to be shrinkable to adapt to different shapes of cuts. In addition it has to enable good machinability while providing resistance to rupture and punctuation. This translates to excellent barrier properties against oxygen, moisture, odour and grease. An oxygen transmission rate of less than 15 cc/m²-d-atm is standard that ensures a long product display time at the retailer. It has to be soft and elastic, yet durable and provide excellent optical properties. PVDC is a shrinkable, tough resin with good barrier properties. PA and EVOH do replace PVDC in some applications. Processed meat is often packed in a sealed tray. A common structure of films in this case is a barrier polymer, a heatresistant and durable printing surface made of PET or PA, a structural layer made of LLDPE or very low density polyethylene (VLDPE) topped by a sealing layer such as EVA, LLDPE or polyolefin plastomer (POP or mPE) or ionomer [699,701]Morris.2016.

Table 1.3.: Functions of common flexible packaging material (Morris 2016; Kaiser, Schmid, and Schlummer 2018, p. 72).

Material	**Sealant**	**Tie-layer Adhesive**	**Barrier**	**Structural Layer**
Aluminium			X	
Paper				X
Titanium oxide			X	
LDPE	X	X		X
LLDPE	X			X
HDPE			X	X
(O)PP	X		X	X
PS				X
(O)PET	X			X
PVC				X
EVA	X	X		X
Ionomer	X	X		
EMA	X	X		
ACR (EAA or EMAA)	X	X		
Tie resin		X		
(O)PA			X	X
EVOH			X	
PVDC			X	
PLA				X

Abbreviations used in the table: ACR (acid co-polymer resin), EAA (ethylene acrylic acid), EMA (ethyl methacrylate), EMAA (ethylene methacrylic acid), EVA (ethylene-vinyl acetat), EVOH (ethylene vinyl alcohol), LDPE (low density polyethylene), LLDPE (linear low density polyethylene), (O)PET ((oriented) polyethylene therephthalat), (O)PP ((oriented) polypropylene), PLA (polylactic acid), PS (polystyrole), PVC (polyvinylchloride), PVDC (polyvinylidene chloride).

1.3. Recycling Challenges Posed by Multilayer Films

A diminished quality of secondary LDPE granulate can manifest itself in different product properties. A comparison to typical virgin material functions as an indicator for product quality, since the granulate is supposed to replace it. For this purpose, the available data of the most frequent LDPE product of an Austrian flexible waste plastic packaging recycling company, is compared with the values of generic virgin LDPE granulate, see Table 1.4. The characteristics for bulk density, Shore hardness and melt flow rate are comparable for both materials. Density and the DSC imply degradation of the polymer and the presence of impurities. These impurities can cause an increase in specific weight and the occurrence of gels and specks in plastic processing, especially when blow-moulding is applied.

Table 1.4.: Comparison of virgin and secondary LDPE material properties.

Characteristic	Unit	Standard	Virgin LDPE[1]	LDPE, coloured[2]
PP content (DSC)	[%]	-	0	<5
Density	[g/cm³]	ISO 1183	0.918-0.927	0.935
Bulk density	[g/l]	ISO 60	330-500	460-520
Shore D	[-]	ISO 868	44-52	48
Melt flow rate	[g/10 min]	ISO 1133	0.15-0.76	0.7±0.3
Gas content	[%]	-	-	<1
Surface moisture	[%]	-	-	<0.04

[1] Note that all data for *Virgin LDPE* derives from UL's PROSPECTOR® materials database 2021. All data from this database is revised to match the same standards, if applicable.
[2] Note that all data for *LDPE, coloured* is derived from a product data sheet provided by the Austrian plastic recycling company.

Per definition, a gel is a defect or agglomeration of degraded polymer or other impurities that disrupts, in this case, the smooth film surface (Kurr 2013, p. 132). A gel can consist of various material. They all have in common to be a variation of insoluble, hard to or infusible material in the extrusion process.
Next to degraded PE accumulations, pigments, fillers, additives, organic residues, inert material and fine grains of metal oxides might occur as gels in LDPE film, according to Spalding et al. 2018. Other plastics than polyolefins (PE, PP), e.g. elastomers, can not be excluded from forming gels as well. This is not surprising at all, taking into consideration the waste management background of the input material and the heterogeneous composition of the content of the yellow bag collection, which is typical input for flexible waste plastic packaging recycling. Figure 1.4 depicts exemplary gels in a clear LDPE film.
These gels are renowned to reduce mechanical properties of a material next to disturbing the physical appearance. The foreign particles act similar to a notch, weakening the endurance and plasticity of the material. This means, that under stress, the material gives way at a particle induced predetermined breaking point, far below the strain limits of an unaffected sample of the same material. Unfortunately, no mechanical properties are published in the product data sheet. Nonetheless, a research paper by Möllnitz et al. 2021, that investigates the mechanical properties of a similar PE product derived from mixed waste collection, reinforces the hypothesis of interdependence of impurities and mechanical properties. To summarize, product quality is highly influenced by the ability and efficiency of the recycling process to remove contaminants and produce an as clean as possible LDPE product output, also in terms of pigments.

1.3.1. Recycling and Sorting Technologies

In comparison to established packaging made of monomaterial, the recyclability of multilayer films is highly challenging. Their indivisible structure made of different thin sheets of varying

	PE-HD	PE-LD	PP-H	PP-HI	PVC	PS	S-B	ABS	ASA	SAN	PA	PBT	PET	POM	PC	PMMA	PSU	PES	PAEK	TPU	(PPE + S-B)
PE-HD	M																				
PE-LD	M	M																			
PP-H	U	U	M																		
PP-HI	M	M	M	M																	
PVC	U	U	U	U	M																
PS	C	C	C	C	U	M															
S/B	C	C	C	C	U	M	M														
ABS	U	U	U	U	M	U	U	M													
ASA	U	U	U	U	M	U	U	M	M												
SAN	U	U	U	U	M	U	U	M	M	M											
PA	C	C	C	C	Z	C	C	C	C	C	M										
PBT	C	C	C	C	Z	U	U	U	U	U	U	M									
PET	C	C	C	C	Z	U	U	U	U	U	U	M	M								
POM	U	U	U	U	Z	U	U	U	U	U	U	U	U	M							
PC	U	U	U	U	Z	U	U	M	M	M	C	M	M	U	M						
PMMA	U	U	U	U	M	U	U	M	M	M	U	U	U	U	M	M					
PSU	Z	Z	Z	Z	Z	U	Z	M	M	M	C	Z	U	Z	M	Z	M				
PES	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	U	Z	Z	Z	M	Z	M	M			
PAEK	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	M	M	M		
TPU	U	U	U	U	C	U	U	M	M	M	Z	U	U	M	M	M	Z	Z	Z	M	
(PPE + S/B)	C	C	C	C	Z	M	M	U	U	U	C	U	U	U	C	U	Z	Z	Z	U	M

Compatibility

- M Miscible
- U Immiscible
- C Compatible with bonding agent
- Z Decomposition

Figure 1.3.: Display of miscibility of different types of plastic. Figure adapted from *Saechtling Kunststoff Taschenbuch* 2013.

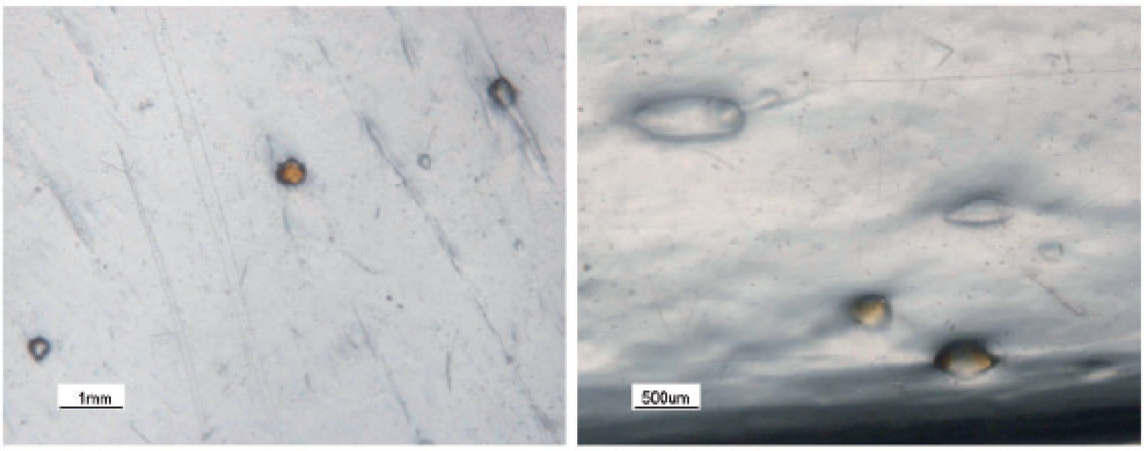


Figure 1.4.: Exemplary gels in clear LDPE film (Spalding et al. 2018, p. 12)

materials with a thickness of 30 µm to 200 µm restricts existing methods to recycle multiayer films on a material level. In the late 90s some patents emerged regarding the idea to use a solvent and, or chemical based agent to resolve the layers, but none of them got realized in a commercial application (Niaounakis 2020, p. 211). Recent developments aim at the same direction of selective dissolution or chemical recycling. BASF was able to recycle PA and PE derived from multilayers in cooperation with Südpack in a pilot project (BASF 2019) or OMV who is engaged in fundamental research to develop a chemical reprocessing of post consumer plastic waste called ReOil process (OMV 2021).

Consequently, mechanical processing and film sorting techniques dominate the processing of flexible plastic packaging film (Niaounakis 2020; Schloegl 2021). They mainly aim at preparing the collected plastic packaging material for further processing in recycling plants by collecting it in homogeneous groups of identical material properties or geometry. Common technologies are air sifter and different screens, such as the vibrating screen or the ballistic screen. They sort particles according to their respective geometries and free the material from contaminants and too small to process particles. However, since there is no stand-alone solution to mechanically separate plastic further beyond their typical properties, multilayer films tend to remain in the product material stream where it disturbs the quality of the manufactured granules due to material incompatibilities. Therefore, the trend in plant engineering shows a clear tendency to use established sorting technologies in combination with optical or electrical systems to achieve the necessary quality. Optical systems stand out due to the ability to detect and eject a variety of polymers at high velocity. They either use visible (VIS) or near infrared (NIR) spectroscopy or a combination thereof. No modern plastic packaging sorting plant can do without cascades of these NIR sorters, often 15-25 pieces are in use per plant. By now, the scope of functionality of NIR sorters is technically limited since they are sensitive to interfering influences and need controlled material conditions.

The material recycling of plastics requires leaps and bounds of innovation in the next five years in order to achieve the environmental policy goals set throughout the EU. This is why the Multilayer Detection project investigates the boundaries of established NIR sensor based sorting systems and its ability to detect and eject multi-layer films but also seeks to improve the recognisability and distinguishability of various other monomaterial fractions from each other in a collaboration of the Chair of Waste Processing and Waste Management of the Montanuniversität of Leoben and the Polymer Competence Center of Leoben, funded by the Provincial Government of Styria.

1.4. Research Goals

The goal of this master thesis is therefore to find answers to the following research questions.

1. "What are the challenges of plastic waste recycling and why are multilayer films not being recycled?"
2. "Which share of the yellow bag is contributed by multilayer films and in which product groups do what kind of multilayer films accumulate?"
3. "How could the recycling of multilayer films contribute to a circular economy?"
4. "How could a design concept for a NIR spectroscopy sorting system look like, so that an identification of multilayer films is possible?"

1.5. Graphical Abstract

This master thesis is divided into three parts and its structure is displayed in Figure 1.5.

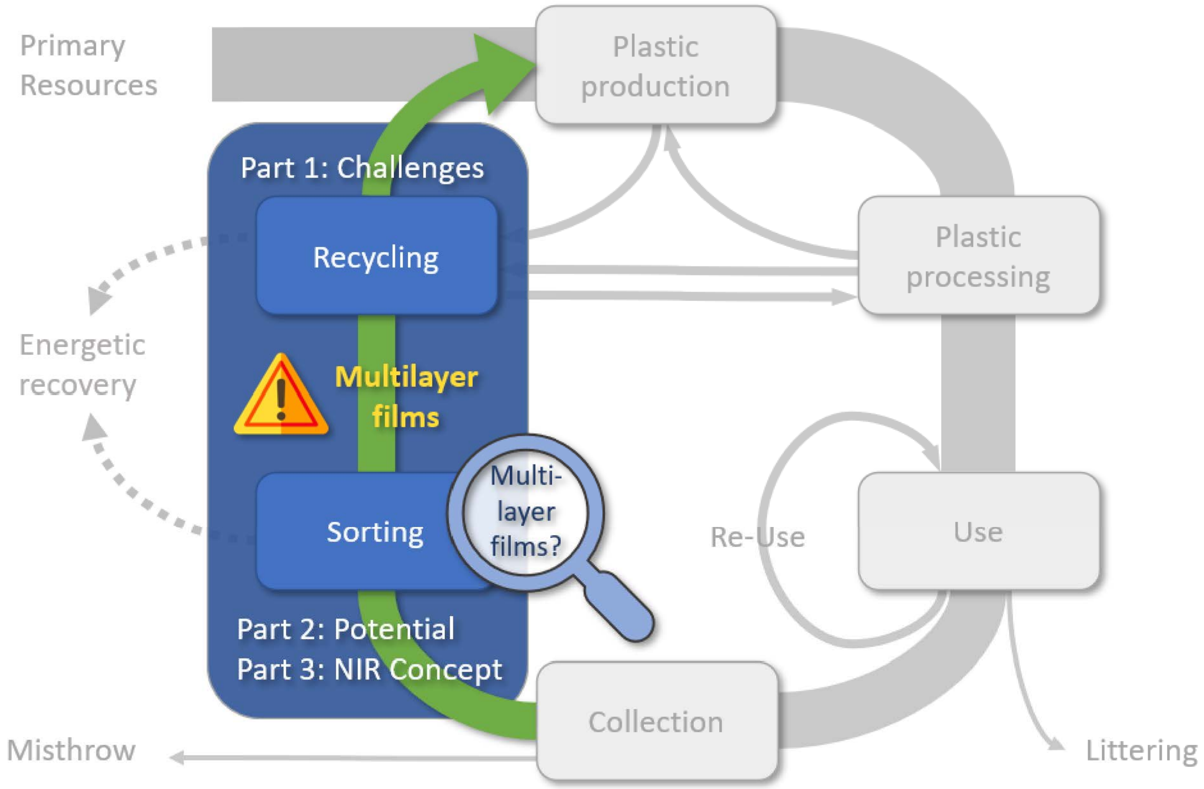


Figure 1.5.: Graphical abstract.[1]

The first part pays special attention to the current challenges that a recycling company of flexible waste plastic packaging has to face at the moment. A material flow analysis of an exemplary recycling plant for flexible waste plastic packaging is established and investigated to assess bottle necks and points out recycling issues for further research. It specifically addresses the role of contaminants such as multilayer films, their impact on secondary raw material quality, and gives an outlook on what measures can be taken in this regard. Part two investigates the prevalence of multilayer films in flexible waste plastic packaging to allow statements about the composition of typical input material of the recycling plant presented in the first part and point out accumulation of mulitlayer films in certain waste product categories. The findings serve as a basis for calculating the recycling potential of multilayer films in the separated collected plastic packaging waste in Austria and up to which degree a targeted sorting of flexible waste plastic packaging can contribute to a sustainable circular economy. Part three investigates the possibilities to adapt an experimental NIR sensor based sorting set-up in order to enhance the detectability of different plastic resins beyond the current limits with special attention to multilayer films.

[1]Exclamation mark icon of graphical abstract published by Freepik on www.flaticon.com

2. Material and Methods

This thesis makes use of different kind of methods to examine the subject from various aspects that are described in the following. A theoretical research facilitates a shared understanding on the disruptive character of multilayer films in modern waste management systems. Whereby the practical approach enables insights on the whereabouts of multilayer films in the Austrian waste plastic packaging collection system and gives way to pursue further research regarding the use of near-infrared (NIR) spectroscopy to identify them.

2.1. Material Flow Analysis of a Flexible Plastic Packaging Recycling Plant

2.1.1. Plant Flow Chart

In this thesis, the establishment of a plant flow chart is going to explain the flexible plastic packaging recycling state-of-the-art by taking a closer look at the plant set-up of an exemplary Austrian flexible plastic packaging recycling plant. The plant flow chart is set up with the support of legacy documents on the recycling plant provided by plant personnel and discussion with experts on-site during plant visits. These visits are also used to validate given information and complement missing data. Finally, a plant flow chart is recorded in writing and presented graphically via a specialized computer software called STAN and serves as basis for subsequent material flow analysis. In this thesis a simplified version is printed due to spacing issues and better readability. STAN is free to use, provided and maintained by the technical university of Vienna (Cencic 15.11.2021).

2.1.2. Material Flow Analysis

By definition, MFA is an analytical method to quantify flows and stocks of materials or substances in a well-defined system (Brunner and Rechberger 2004). MFA bases on the fundamental scientific principle of mass balance, which states mass cannot vanish. Therefore, the principle of mass conservation applies. Hence, a loss free system is assumed. This delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. Through balancing inputs and outputs, the flows of goods become visible, and their sources and sinks can be identified. With the establishment of material balances one is able to either check the consistency of the data in cases where all flows are known (input = output ± storage) or it can be used to determine one unknown flow per process, see Figure 2.1.

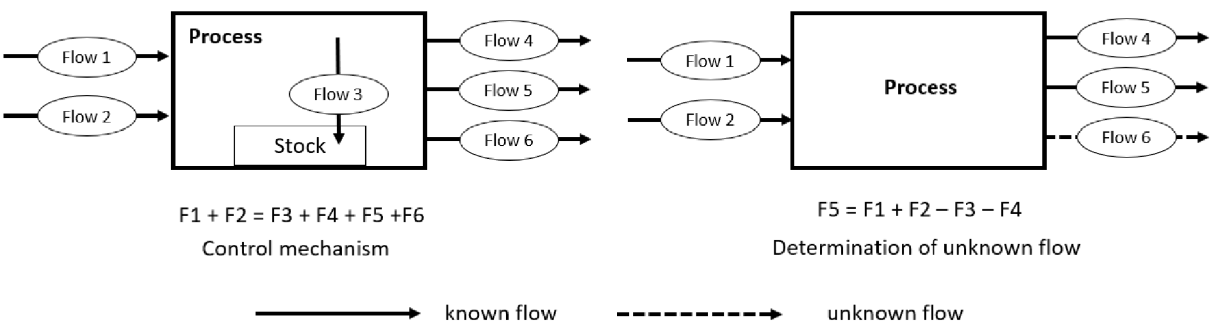


Figure 2.1.: Application of mass balance principles in MFA. Figure based on Brunner and Rechberger 2004.

The material flow analysis (MFA) aims to merge all provided relevant information on input, output and by-products of the exemplary recycling site. The calculation of material transfer coefficients allows to identify and fill gaps of knowledge on unknown material flows and provides insights on the inner processes of the recycling plant. The results are presented in a graphical way on the basis of the prior established plant flow chart. Material flows and transfer coefficients are calculated using Microsoft Excel. The collected data are evaluated with the support of specialized computer software for substance flow analysis called STAN. The detailed calculation sheet for each production line can be found in the appendix A.

System Definition

The system of the material flow analysis is limited by the borders of the building in which two production lines of the exemplary flexible waste plastic packaging recycling plant are located. These lines get selected, because due to their differing age (1997 and 2007, with an upgrade in 2015 for the latter), they very well represent the historical development of waste plastic processing and the difficulties that come with it. Production line 2 was under reconstruction at the time of the study. It is therefore not part of this survey.
The inspection is done on a goods level, considering the material flows of flexible waste plastic packaging and the by-products generated by the recycling process. The aggregates themselves are considered as black boxes. No sinks or wells do exist. Auxiliary material such as electricity, energy and water consumption are explicitly not part of the material flow analysis. The moisture content of the post-consumer plastic waste is also not taken into account. All material is considered to be dry.

Data Basis

The collection of data has taken place in 2018, hence, all presented information refers to that year. The data for the material flow analysis is based on the revision of provided documents on input and output by the plant operator. Unknown data flows are calculated if possible. No tests or experiments are carried out in situ by the author. It is complemented by the collection of information during interviews with experts and plant visits on-site. Therefore, it relies on the correctness of documents and verbal information. For the calculation of unknown material flows the following assumptions are made: If one flow at a single process is unknown, it gets calculated according to the mass preservation principle. If more flows are unknown, estimation by the plant personnel is used to permit calculation. If the assumed quantity of a material flow is estimated to be a fraction of less than one percent of the input, the stream is set to zero.

Input Material

In general, the input material consists of pre-sorted compressed post-consumer plastic waste. Pre-sorting is done by specialized sorting companies and is not part of the survey. Depending on the material, the bale is either stored in open air or in an area protected by a flying roof until a hauler loads the opened bale on the feeder belt. The input material is categorised according to the specifications for light packaging waste published by Altstoff Recycling Austria (ARA), a non-profit company responsible for the Austrian packaging compliance scheme. This is done independently of the country of origin, even when the input material comes from the international perimeter of 200-400 km of the plant. The definition of the different input material is listed in Table 2.1. Apart from the input at the front end of the recycling plant, other sorts of input are added at the end of the recycling process right before or during the extrusion process of the LDPE flakes. Clean plastic wastes, such as industrial plastic production waste or internal recycling material e.g. laser or band filter cake, are also blended in at this step. If necessary, spare virgin LDPE material or small amounts of black masterbatch are added to the plastic melt.

Table 2.1.: Description and definition of the input material based on specifications by ARA

Nr.	Material	Description	Contaminations
420	PE foils mixed	LDPE and/or LLDPE packaging, clear, translucent, coloured or printed on, only water soluble contaminants	<0.05 w-%: PA, PVC-foils and in total <5 w-% of heavily contaminated (L)LDPE foils, or (L)LDPE foils with non-PE adhesives less than 1 % of total foil surface, chemical or fertilizer bags
421	LDPE foil natural, blank	Non-coloured, blank LDPE packaging, blister foil or foil with printed on repetetive recycling symbol not more often than every 50 cm; else 422	<0.05 w-%: PA-, PVC-foils and in total < 5 w-% of chemical or fertilizer bags
422	LDPE foils coloured, printed on	colourful, printed on LDPE packaging	<0.05 w-%: PA-, PVC-foils in total and <5 w-% of transparent LDPE packaging (421) and in total <5 w-% of chemical or fertilizer bags
423	(*)		
429	PE foil mix, shopping centre	Mix of fully emptied LDPE foils and LLDPE foils clear, transparent, coloured, or printed on	<0,05 w-%: PA-, PVC-foils and in total <5 w-% of heavily contaminated (L)LDPE foils, or (L)LDPE foils with non-PE adhesives and less than 1 % of total foil surface
430	PE foil mix, commercial	Mix of fully emptied LDPE foils and LLDPE foils clear, transparent, coloured and printed on. With LLDPE packaging up to max. 20 w-%	<0.05 w-%: PA-, PVC-foils in total <5 w-% of straps, non-PE adhesives, non-water-soluble contaminants, HDPE, PP, blisters, molding parts, fruit nets, expanded PS and others
755	LDPE virgin material	Production waste of plastics manufacturer	None

The latter is responsible for a full black colour of the recycled lentils. This input is assigned to number 755 and is an exemption from the ARA nomenclature.

By-products

Table 2.2 lists all by-products of the plastic recycling process put in chronological order according to their occurrence along the recycling process, their respective production line and their whereabouts. Typical by-products of the process are metal waste, mixed waste, reject, calorific fraction, waste water, sludge, humid air, tar oil and filter cake. Please be aware, that the term by-product is used in a process engineering context and should therefore be understood as distinct from the term used in waste legislation.

Metal Waste Metal waste is a heterogeneous mixture of different iron and non-ferrous scrap. The composition has varying shares of wire used for bailing, smaller ferrous metal scrap from

Table 2.2.: Description and definition of by-products

By-product	**Waste code**	**Origin**	**Line**	**Recipient**
Metal waste	35103	Material reception Mechanical Treatment Magnetic separation Extrusion Workshop	L1, L3 L1, L3 L1 L1, L3 -	Contractor Contractor Contractor Contractor Contractor
Mixed Waste	91101	Washing Density sorting	L1, L3 L1, L3	Contractor Contractor
Reject	91103	Screen undersize Density sorting	L1, L3 L1	Co-incineration Co-incineration
Calorific fraction	57129	NIR sorting 1 NIR sorting 2 Manual sorting	L1 L1 L1, L3	Co-incineration Co-incineration Co-incineration
Waste water	-	Washing Density sorting	L1, L3 L1, L3	Sewage plant Sewage plant
Sludge	94502	Density sorting Sewage plant	L1 -	Contractor Contractor
Humid air	-	Drying	L1, L3	Atmosphere
Tar oil	54201	Extrusion, APC	L1, L3	Contractor
Filter cake	NAV 138	Extrusion	L1, L3	Co-incineration, internal recycling

the magnetic separation and stout metal scrap of wearing machines parts or the on-site workshop. The metal scrap is handed over to an contractor for recycling.

Mixed Waste Mixed waste is an umbrella term for every material that is removed during washing or by density sorting and refers to a mixture of mostly non-plastic and non-PE material. It is comprised of organics like cardboard, paper or wood chips, inorganics such as small stones, ceramic shards, glass and non-ferrous metal alloys, mostly aluminium.

Reject Reject is the term for too dense and heavy plastic material that is rejected by density sorting. A small fraction of it is material, which is too small to pass the vibrating screen or the screening drum. It is highly calorific and therefore a valuable feedstock for co-incineration. Since the heavier plastic particles that get rejected by density sorting very likely consist of PVC, the reject fraction is a sink for chlorine. On average, it inhibits 0.6-1.2 % chlorine. The contractor typically is allowed to demand a gate fee if chlorine is too high.

Calorific Fraction Calorific fraction is defined by the recycling plant as high calorific non-PE material. It describes material that is either removed manually by personnel or automatically by the NIR-sorting cascade of line 1 and is dedicated to serve as residue derived fuel (RDF) for a co-incineration plant. The following materials are removed at the sorting cabins: Compound films, elastomers, unemptied bags, biogenics, strongly pigmented or black material, high density PE, objects and films made of PP, fibre-enforced films, inerts and metal parts. Other contaminants such as PA, PVC or PET are not especially aimed for at the manual sorting, because they are presumed to be removed by the density sorting section of the recycling process. Two continuous NIR-sorters designed to operate as Rougher and Cleaner target the same material but they are less restricted by throughput and cleanliness. At the first stage, a positive sorting algorithm targets all objects made of PE. At the second stage, a negative sorting algorithm clears the valuable PE product stream of all remaining contaminants.

Waste Water Waste water is process water, that has been in contact with the recycling material. Waste water is produced at the washing section and density sorting. The water drags along adhering impurities of the feedstock. Consequently, it is a critical factor for product quality. Besides antispumin to diminish the foam, no other detergents are used at the washing process. Process water is recirculated multiple times before it is led to the sewage plant.

Sludge At the sewage plant of the recycling site the used process water is freed of suspended matter. The recovered sediments form a sludge, which is given to a contractor.

Humid Air Drying of the plastic flakes results in the evaporation of residing moisture. The humid air is filtered and emitted to the atmosphere.

Tar Oil The exhaust gas of heating and melting the plastic flakes at the extrusion process is sucked and quenched at the downstream air pollution control (APC) unit. The resulting condensate or tar oil, is a mixture of different organic compounds, that is taken care of by a contractor.

Filter Cake During the extrusion process the heated plastic melt is forced to pass filters of a mesh width of 100 to 150 micrometres. Larger particles, most likely undesired pollutants, are withheld. Embedded in a matrix of PE, they build up a filter cake. Depending on the degree of contamination, the high PE content allows for the reuse of the filter cake as feedstock (NAV 138) of the recycling plant. If recycling is not possible it is instead co-incinerated.

Figure 2.2.: Typical products of the recycling plant. From left to right: LDPE translucent, LDPE coloured and LDPE black (+2 % black).

Products

The products of the recycling plant are different kinds of LDPE granulate. LDPE is typically flexible and hard-wearing, very resistant to chemicals, gas tight and in its natural state colour-, odour- and tasteless (Domininghaus et al. 2012). Properties that make it the preferred feedstock for the manufacturing of films of all kinds. The current main application of the produced LDPE granulate is the production of waste bags. The three most common product categories are LDPE coloured, LDPE translucent, and LDPE black. The heterogeneous mix of differently coloured input objects causes a varying pigmentation of the plastic melt. Figure 2.2 depicts examples of the three most common products of the recycling plant.
A mixture of rheological, physical and thermal performance values serve as key metrics for product quality. In total, the following subset of tests is conducted by the quality lab to ensure compliance with the output specifications of the products: Differential scanning calorimetry (DSC), viscometry with melt flow rate (MFR), shore hardness test, assessment of density and bulk density, testing of surface moisture, a gas cavity test, and a lab scale blow moulding combined with visual inspection. The main task of them is either to determine the amount of non-PE material in the LDPE products, test material properties, that are indirectly connected with the prevalence of non-PE material, or necessary technical parameters for reprocessing the granulate. Typical output specifications of the products are listed in Table 2.3. The most important methods used to gain the presented data with special relevance to plastic recycling are briefly described in the next paragraphs. More information on polymer testing can be found in specialized literature, e.g. "Polymer Testing" by W. Grellmann (Grellmann and Seidler 2013).

Table 2.3.: List of products and their typical output specification according to the plants product data sheet.

Characteristic	Unit	LDPE natural	LDPE translucent	LDPE coloured	LDPE light coloured	LDPE black (+0 %)	LDPE black (+2 %)
PP content	[%]	<1	<1	<5	<1	<5	-
Density	[g/cm³]	0.920	0.925	0.935	0.935	0.945	0.945
Bulk density	[g/l]	450-500	450-500	460-520	460-520	460-520	460-520
Shore D	[-]	15:48	15:48	15:48	15:48	15:49	15:49
Melt flow rate	[g/10 min]	0.5±0.2	0.5±0.3	0.7±0.3	0.7±0.3	0.7±0.3	0.5±0.3
Gas content	[%]	<1	<1	<1	<1	<1	<1
Surface moisture	[%]	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Black	[%]	0	0	0	0	0	2

Key Performance Indicators

Specific material flows derived by the material flow analysis are used as foundation to calculate key process indicators (KPI) in order to evaluate the efficiency of the presented recycling process. These figures provide insights on inner processes and serve as starting point for further investigation. To evaluate the recycling process itself, the productivity rate (PR) and the recycling efficiency (RE) are calculated as benchmarks, shown in Equation 2.1 and Equation 2.2. PR is a measure of processing effort and material intensity. It establishes a relationship between manufactured products and the resources they require. Its range is between 0 % and 100 %. Low values of PR imply a high employment of machinery with low effective output, whereas large values indicate a high degree of efficiency. RE is a measure of recycling efficiency of a process. It assesses the ability of a process to extract a specific good or substance from a material stream. Therefore, it can be considered as yield. It also ranges from 0 % to 100 %. High values of RE indicate great sorting efficiency. Here, RE is used to calculate to what extent all of the plastic material that enters the recycling plant is actually recycled to LDPE granulate. For a complete picture in the evaluation, attention must always be paid to both key figures and their interaction. If RE is high, yet PR is low, a considerable amount of machinery is used to successfully remove the major part of the desired high value material. A process of this kind may be expensive, but can still be considered as economically reasonable in combination with high revenue products e.g. gold recycling.

$$PR = \frac{\sum \text{Products}}{\sum \text{Input}} * 100\% \tag{2.1}$$

$$RE = \frac{\sum \text{Products}}{\sum \text{Input plastics}} * 100\% \tag{2.2}$$

Expert Interviews

The result of mass flow analysis and the KPIs on plant performance serve as basis for fundamental discussion comprising different stakeholders of the plant site. Goal is to collect all the subjective impressions and opinions on challenges concerning waste plastic packaging recycling after presentation of the findings. A transverse section through all management levels ranging from specialist workers, quality manager to plant operator and plant owner ensures a broad field of perspectives. Overall, five persons of the investigated site got interviewed. The expert interviews are also carried out in 2018 either in person during the plant visits or via telephone. To guide the interview, a subset of questions was prepared in advance to fit the position the interviewee has been in. Yet, the interview was intentionally kept very open in order not to interrupt the flow of the experts. All opinions are collected, clustered and transcribed analogously in a summarizing manner. The result reflects the subjective perceived challenges of operating a flexible waste plastic packaging plant in the context of waste management and are not the opinion of the author.

2.2. Hand Sorting Analysis of a 2D Fraction from an Lightweight Packaging Sorting Plant

The hand sorting analysis of the pre-sorted, two dimensional flexible waste plastic packaging, derived from the yellow bag collection system, results in the assessment of 842 objects, with a total weight of 10.4 kg. Every object of the material described in Section 2.2.1 is visually inspected, identified, weighed and categorised. Two complementary categories, listed in Table 2.5, are assigned to every object of the flexible waste plastic packaging sample next to a unique sample identification (ID) and a brief object description. Table 2.4 shows an example for the labelling of a categorised object.

Table 2.4.: Exemplary label of categorised sample objects.

ID	Description	Category 1	Category 2
B3	Clever Saltsticks	Primary food packaging	Snack metallised

Category one subdivides the objects according to the fact if the packaging is, or is not, in direct contact with food or a non-food product. For example an object labeled as primary food packaging is a packaging in direct contact with the packed food inside. A secondary food packaging is a supplementary wrapping of already packed food e.g extra pouch bag for single wrapped sweets. Category two additionally connects the objects with their respective product group. If neither category fits, the object is assigned to a generic group of bags or foils. Excluded of the survey are objects of a size smaller than 40 mm. This includes bits and shreds of unspecific plastic films or single packaging of sweets. Also excluded is material that is used as wrapping of discarded food or waste coffee caps and misthrow, e.g. metal cans, bottle caps. Additionally, flattened trays made of polyethylene therephthalate (PET) are not part of the survey as they do not match the criterion of being two dimensional flexible packaging. Due to hygienic reasons, any kind of flexible medical waste plastic packaging is excluded as well.

Table 2.5.: Definition of sorting categories

Category 1	**Category 2**	**Example**
Primary food packaging	Bakery products	Bread, rolls, pastery
	Coffee	Coffee bags
	Dairy	Sliced cheese, yogurt lids, mozzarella sachets
	Dry food	Rice, noodles, cereal
	Fresh produce	Packaging of various fruits and vegetables
	Frozen food/convenience	Frozen vegetables, convenience food and dough
	Household packaging	Bags with zip fastener, freezing bags, cling film
	Meat	Meat, sausages, cold cuts
	Snack metallised	Salty and sweet snacks with metallic coating
	Snack uncoated	Salty and sweet snacks without metallic coating
Secondary food packaging	Beverages	Wrapping of six-packs
Primary product packaging	Construction/workshop	Cement bags, tools, oil
	Dry pet food	
	Garden	Soil, mulch, bark chips
	Household products	Clothes bag, toner, clothing
	Sanitary products	Wrapping of toilet paper, kitchen roll
	Toys	Lego sachets
	Wet pet food	
Secondary product packaging	Gift wrapping	Wrapping paper, ribbons, cellophane
	Mail order	Mailing bags, air cushion foil, bubble wrap
Bags	Generic bags	Transparent or colored single use multi-purpose plastic bags
	Carrier bags	Classical carrier bags
Foils	Generic foils	Pieces of various unspecific foils

The results are documented and evaluated by means of frequency distribution depicted in histograms, Pareto diagrams and heat maps.

Furthermore, the presence of recycling marking on flexible plastic packaging is recorded. A smaller subset of the sample (N=239) is inspected if they are marked with either the standardized symbols for plastic resins as proposed by Austrian Packaging Ordinance (BMLFUW 2014).

2.2.1. Sample Description

The weight of the flexible waste packaging sample is 10.4 kg and the overall weight of the yellow bag is 39.3 kg. The sample is not representative for any larger population. In order to be able to make valid statements about the total light weight packaging material stream three qualified random samples of at least the same size as the present sample are necessary (Austrian Standard 2012). The same statement applies to the two dimensional fraction of the sample. The material for the sorting analysis originates from the waste collection system for disposed light plastic packaging named "yellow bag". The yellow bag is a typical collection system for waste plastic packaging in rural areas with a low population density. The sample is provided by the waste management company Brantner[1], located in Lower Austria. The time period of collection is the first quarter of 2021 in Lower Austria. How the sample was taken is unknown to the author. A share of the examined plastic waste is significantly correlated to Christmas, since the sample of the yellow bag was collected at the end of January. This manifests in increased occurrence of toy packaging, single packaging of sweets (Lindt balls), delicacies (smoked fish) and gift wrapping. Another prevalent perception is the apparent effect of the recent Covid-19 pandemic and the continuing lockdown. People stay more at home, cook increasingly for themselves (fresh produce and convenience food) and are partially forced to do online shopping (mailing pouches and protective material). The ban on plastic bags seems to have already taken effect too, since few are to be found in sample. Figure 2.3 gives an exemplary impression of the flexible waste plastic packaging.

Figure 2.3.: Exemplary flexible plastic packaging sample material from the yellow bag collection in Lower Austria, provided by Brantner.

2.2.2. Equipment

The investigated sample was manually sorted into fractions, see Section 2.2, and each fraction was weighed using a digital scale (KERN 440-49-N, precision 0.1 g).

A randomly picked subset of the sample objects was analysed for material composition using attenuated total reflectance Fourier-transformed infrared spectroscopy (ATR-FTIR, Perkin Elmer, diamond crystal, 650 cm-1 to 4000 cm-1, spectral resolution 4 cm-1, 4 runs per sample) by the Polymer Competence Center of Leoben (PCCL).

To validate specimen to be monomaterial a differential scanning calorimeter (DSC 4000, Perkin Elmer) was used to inspect two samples, consisting of three discs each (6 mm diameter, 3 and 7 mg) of every material via auto sampler at (PCCL). The Parameters used are: Nitrogen purge, 50 ml/min; Heating rate, 10℃/min; 1st Heating, 25 to 270℃; Cooling, 270 to 25℃; 2nd Heating, 25 to 270℃.

[1] Brantner Österreich GmbH, Dr. Franz-Wilhelm-Straße 2a, 3500 Krems an der Donau

2.2.3. FTIR-ATR

FTIR-ATR is an easy, quick and non-destructive method which is common in quality assessment and goods inspection (Günzler and Gremlich 2003). A subset (n=143) of random objects of the total two dimensional yellow bag sample (n=842) is subject to further examination using Fourier-transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) to identify multilayered film. It is used to obtain an infrared spectrum of absorption of a sample which reflects the characteristic chemical properties of the material. The tests are performed by the external laboratory and project partner Polymer Competence Center Leoben (PCCL). The spectra are then visually inspected if and how they resemble reference spectra in order to identify its molecule structure and thus, the specific type of polymer.
Before the measurement every sample gets cleaned and cut into fitting pieces. Three test points are assigned to each side of the fragment to ensure reliable results. Finally, for every side, the identified type of polymer and the thickness of the film itself are noted. Samples, with differing results of polymer type for the front and the back, are confirmed to consist of at least two different layers of polymer films, and are therefore considered to be justifiably labelled as multilayer films. They are marked with (1). Samples, where the FTIR-ATR analysis results in consistent material for front and back, are marked with (0). Ten specimens were lost and therefore not subject to the FTIR-ATR analysis. These samples are marked by a blank entry in the result columns (IN) and (OUT). Their weight is excluded from any further calculation. Another ten samples were impossible to identify accurately. They are marked with a question mark (?) in the result column.
Depending on sample conditions, refractive index, and beam angle, FTIR-ATR has a penetration depth of a couple wavelengths (typical 1-2 µm) (Smith 2011; Griffiths and Haseth 2006). It is therefore more suited to inspect the surface properties of thin film samples than to identify multiple layers of polymer film. However, it is suited to indicate them. It has to be noted, that a sandwich structure consisting of PE-X-PE, with X being any kind of other material, is not recognized as such. This renders the method prone to false negative results and the dark figure might thus be higher than investigated. Therefore, ten specimen assessed as monolayer material are sent to PCCL for reevaluation with differential scanning calorimetry (DSC).

2.2.4. Differential Scanning Calorimetry

DSC is often used for quality assurance at polymer manufacturing. It allows the identification and quantification of polymers by looking at the melting behaviour of the materials. The presence of melting peaks at different temperature indicate different materials. Unlike FTIR, which can be considered non-destructive, DSC is destructive. Here it is used to evaluate the monolayer status of ten specimen. Test specimen are put on small tray in a lab oven, that heats linearly with a specific heat flux in two runs. After the melting during the first heating run a better contact between material and pan can be achieved. The second heating curve has been used to identify the melting peaks of each material. Any change of the test sample in correlation with temperature e.g. melting, results in an observable change of heat capacity. A concave shape in the curve indicates an endothermic process (such as melting), whereas a convex shape indicates an exothermic process. A uniform course of the curve with the material-specific characteristics of the identified monomaterial is expected. Deviations are compared to curves of other characteristic material. If a suspected PE monolayer material exhibits e.g. typical melting peaks of PP material in addition to PE, it is assumed to be multilayer.

2.2.5. Assessment of Recycling potential and Estimated Contribution to the Austrian Plastic Packaging Recycling Efficiency

This section is about how to estimate the recycling potential of multilayer films and their ideal contribution to the Austrian plastic packaging recycling efficiency. The figures for the estimation are based on the MFA of the Austrian waste plastic packaging management published by Van Eygen 2018, displayed in Figure 2.4, and will be complimented by the findings of the hand sorting analysis. By taking advantage of the comparability of the two dimensional foil fraction derived from the hand sorting analysis and the fraction of the MFA called "Films small" shown in dark blue in Figure 2.4, since it refers by definition of Van Eygen 2018 to films with a total area of less than 1.5 m², assuming general statements can be made for Austria. This small films fraction sums up to 52,000 tons, which is equivalent to a share of 30 w-% 2D material in separately collected waste (SCW).

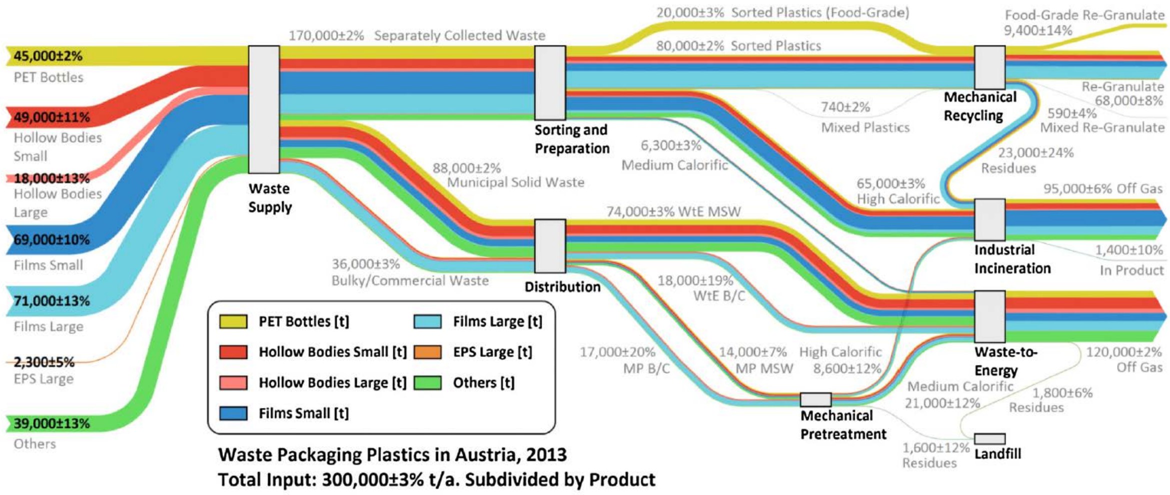


Figure 2.4.: Austrian waste plastic recycling routes, subdivided by product category. Special remark goes to the category "Films Small" referring to films smaller than 1.5 m² in dark blue, comparable to the hand sorted yellow bag sample. Figure by Van Eygen, Laner, and Fellner 2018.

Combining the values of the material flows of the recycling routes of flexible plastic packaging with the findings of the multilayer film in the two dimensional yellow bag fraction, gives the ideal recycling potential of multilayer films. Since multilayer films are part of the small films fraction it is assumed that multilayer films reflect their behavior and take the same recycling routes. 24 w-% are subject to a mechanical recycling process, presumably disrupting it, and 76 w-% of multilayer films are incinerated, accordingly. Finally, three idealized scenarios are evaluated with respect to their influence on the Austrian plastic packaging recycling efficiency which is currently at 25.7 w-% since 77,000 tons of 300,000 tons of waste plastic packaging are mechanically recycled in 2019. Figure 2.5 gives an overview of the different scenarios.

Scenario 1 – Business as usual

	Multilayer films	Small films
Recycling		X
Incineration	X	X

Scenario 2 – New technologies

	Multilayer films	Small films
Recycling	X	X
Incineration		X

Scenario 3 – Zero Waste

	Multilayer films	Small films
Recycling	X	X
Incineration		

Figure 2.5.: Different scenarios for the assessment of the contribution of multilayer films to the Austrian plastic packaging recycling efficiency.

Scenario 1 Scenario 1 reflects the business as usual. Small films follow their respective recycling routes unchanged. 24 w-% (12,280 tons) of small films derived from SCW are mechanically recycled, the rest is co-incinerated. However, innovation accelerated by project Multilayer Detection enables detection and targeted ejection of multilayer films. Since no dedicated recycling route is available all multilayer films are assumed to be subject to industrial incineration.

Scenario 2 In scenario 2 substantial innovations are made. Further progress of recycling techniques to detect, eject and recycle multilayer films are available and in use on an industrial scale. Consequently, all multilayer films are subject to material recovery. Small films follow their respective recycling routes unchanged. 24 w-% (12,280 tons) of small films derived from SCW are mechanically recycled, the rest is co-incinerated.

Scenario 3 Scenario 3 reflects a zero waste future. New technologies to detect, eject and recycle multilayer films are available and in use on an industrial scale. In addition, those innovations tap the recycling potential of small films by enhancing sorting depth of legacy sorting systems e.g. NIR sorting. Ideally, co-incineration of small films and multilayer films is fully replaced by mechanical recycling.

2.3. Considerations Regarding a Design Concept for an Experimental NIR Sensor Based Sorting Stand

2.3.1. Literature Research

A theoretical investigation via literature research on Boogle, Scopus and Google Scholar provides necessary general knowledge and understanding of the role of the fundamental functionality of NIR spectroscopy in waste plastic packaging recycling facilities. All collected sources of literature are assessed and evaluated with regard to their relevance to exploit features of multilayer films or NIR spectroscopy itself to enable their detection. Information, that has been assessed as valuable got processed in written or graphical form. Their content has been compared and linked to each other. The condensed knowledge on NIR spectroscopy then serves as basis for further considerations on how to adapt the given set-up of an experimental NIR sensor based sorting system to enhance the NIR signal to give cues on how to enable multilayer film detection. Table 2.6 lists all included sources of literature concerning NIR spectroscopy and material properties of multilayer films. Overall, 21 literature sources are included in this part of the thesis.

Table 2.6.: Literature sources

Type of literature source	Number
Journals	9
Theses	2
Reports	2
Books	6
other	2
Total	21

2.3.2. The NIR Sensor Based Sorting Stand

The Chair of Waste Processing and Waste Management of Montanuniversitaet Leoben, has an experimental sensor based set-up, designed by Binder+Co AG, in operation. This sensor based sorting system serves as experimental set up to test different NIR sorting models suitable to distinguish different flexible waste plastic packaging types from multilayer films. For more information, please refer to Chapter 1 - Multilayer films. A schematic representation of the experimental set-up is shown in Figure 2.6. It features a hyperspectral imaging NIR chute sorter based on a HELIOS NIR G2-320 hyperspectral imaging system by EVK [2] (EVK DI Kerschhaggl GmbH n.d.) in pushbroom configuration. The detector is an InGaAs matrix sensor with a spatial resolution of 312 pixels and a spectral resolution of the sensor of 9 nm. The sensor covers the full width of the chute (width=500 mm), which results in an analyzed lateral pixel width of 1.60 mm. The pixel length varies according to the conveying speed and the sampling rate. The detector has a spectral range from 930 nm to 1700 nm at a sampling rate of 476 Hz and an exposure time of 1.800 µs. Illumination of the samples is achieved by using a set of halogen lamps (tungsten filament). The emitted light interacts with the sample material and is reflected, absorbed and/or transmitted.

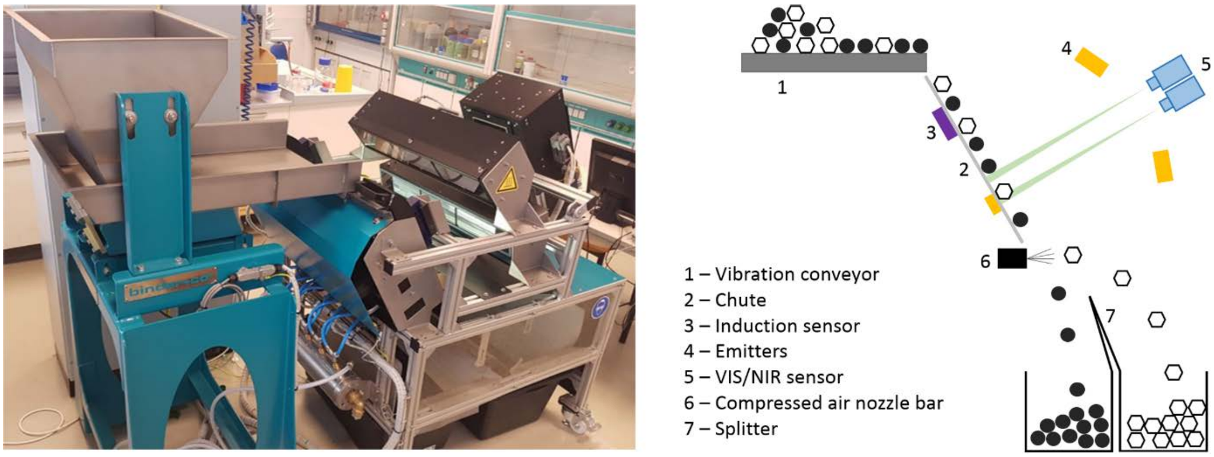


Figure 2.6.: NIR sensor based sorting stand (Küppers 2019).

[2]EVK DI Kerschhaggl GmbH, Josef-Krainer-Straße 35, 8074 Raaba, Austria

3. Results and Discussion

3.1. The Challenges of a Flexible Waste Plastic Packaging Recycling Plant

The goal of this chapter is to answer research question 1.

1. "What are the challenges of flexible plastic waste recycling and why are multilayer films not being recycled?

3.1.1. Description of the Recycling Process

In principle, every plastic recycling process consists of the same five core components and so do process line 1 and line 3 of the exemplary plastic recycling plant. The core components are (1) mechanical pre-processing, (2) washing, (3) density separation and sorting, (4) drying, and (5) extrusion. However, line 1 and line 3 differ from each other in the use of different aggregates when it comes to mechanical pre-treatment, density sorting and drying. The used technologies are listed in Table 3.1 and also shows the historic differences between the lines.

Table 3.1.: Overview on technology differences in the process set-ups of line 1 and line 3. Abbreviations: AS (automatic sorting), MS (manual sorting).

Process step	Line 1 - AS	Line 1 - MS	Line 3
Mechanical pre-processing	Pre-shredding Over-belt magnet Vibrating sieve NIR-sorting cascade	Bale breaker Manual sorting Pre-shredding	Bale breaker Manual sorting Pre-shredding Drum screen
Washing	Sedimentation tank Washing mill Cleaning centrifuge Washing silo		Sedimentation tank Washing mill Cleaning centrifuge Washing silo
Density sorting	Hydrocyclone batteries Reject recovery		Separating basins
Drying	Drying centrifuge Screw press Drying unit: Zig-zag build		Centrifuges Screw press Drying unit: Silo-like build
Extrusion	Extruder with cutter compactor Band filter Two laser filters		Extruder with cutter compactor Two band filters Laser filter

Production Line 1

Line 1 is in operation since 2007 and has a capacity to recycle almost 18,000 tons of input per year. Experiences made with its predecessor, line 3, have been translated into innovations for its set-up. In respect to its capacity, it can be considered as the main recycling line of the plant. In 2015, the mechanical pre-treatment got an update. Since then, the mechanical pre-treatment has been running on two parallel lines. On the one hand, the pre-sorting of plastic

waste is conducted manually in a sorting cabin and on the other hand, a fully automated two-stage NIR sorting cascade takes care of the task.
On the manual line, the bales are first freed from the stabilisation belts and fed to the bale ripper with a loader. The now approximately DIN A3 sized pieces are manually freed of contaminants by trained personnel. An aggregate with the power of 250 kW reduces the particle size to 26-30 mm in a pre-shredding step.
In the automated lane the bales are first freed from the stabilisation belts too. Subsequently, the material is shredded and remaining iron parts get removed by an over-belt magnet. Since the automatic NIR sorting can only analyse and sort material above a certain grain size, everything runs over a vibrating screen with a 30 mm mesh beforehand, in order to reduce the fine grain content. The NIR sorting consists of a cascade of two sorting units. First, positive sorting removes the accepted particles by the sorting algorithm. This stream is then freed of the remaining contaminants via negative sorting. The removed impurities and problematic materials are collected, pressed in a baler and sold as a calorific fraction.
The pre-sorted and commuted particle streams from both, the automated and the manual-mechanical preparation lane of line 1, are combined in the settling basin. This is where the material comes in contact with process water for the first time. Here, heavy impurities and adhering contaminants are removed via sedimentation. Next up is the washing mill. In the mill, the plastic parts are softened and impurities get dissolved. The latter, including adhesives, get removed by the cleaning centrifuge or by the successive washing silo. The washing silo of line 1 has a power of 250 kW and is designed redundantly. While one silo is unloaded, the other is being fed, which results in a continuous process despite batch wise filling.
The subsequent separation step is a combination of mixing chests and hydrocyclone batteries. The latter have a capacity of 150 m³/h. The first is responsible for the homogenization of the material and the latter for the density separation. The different streams of the hydrocyclone battery 2 and hydrocyclone battery 3, with material above the defined separation density, also referred to as “accept”, are united at a vibrating drainage screen, that is placed above the fresh water tank. So, excess water is returned to the process water. The dense material, also referred to as “reject”, from hydrocyclone battery 1 to 3, is unloaded onto another vibrating drainage screen above another water basin, named hydrocyclone basin. Particles heavier than water, sediment. This sediment is composed of various inert materials such as glass, ceramics, stones, light metal particles or polymers of higher density, such as PVC, next to occasional wrongly ejected valuable plastic particles, that get dragged along with the rejects in the basin. Due to their low density, the main share of residing light LDPE flakes tend to accumulate on the surface of that basin. They get skimmed and led to hydrocyclone battery 3 for material recovery. Here, it is merged with potentially valuable particles from line 3 before entering the aggregate. As a result, additional 7-13% accept material is recovered from a supposed waste stream. The remaining heavy sediment is conveyed and drained by a screw press, which is installed at the bottom of the basin. It drains the reject before it feeds it to the off-site reject container via a conveyor belt.
Since the degree of humidity must be kept as low as possible for the extrusion process, all accepted material is conveyed to a screw press and a drying centrifuge, whether it comes from the material recovery lane or not. The installed screw press is equipped with a perforated screen with a mesh width of 3 mm and has a power of 18 kW. After this, the flakes are passed through a heat exchanger for drying. The heat exchanger is designed to act like a zig-zag separating unit with a thermal capacity of 250 kW. It uses as heating medium hot water at 90℃–100℃ to heat the drying air to 80℃. A fan blows the material through zig-zag shaped shafts from bottom to top. The first shaft is used to separate parts that are too heavy to be carried along by the airstream. The rest is dragged along. On their way up and through the shafts, the hot air dries the plastic flakes.
Finally, the polyethylene-rich stream, which is clean, free from impurities and dry, passes through a storage silo to the extruder. While passing through, necessary additives (virgin ma-

terial, filter backwash, etc.) are added as needed. At the beginning of the extrusion process, a cutter compactor compresses, homogenises and heats the plastic flakes. Any exhaust gas is sucked-away and quenched. The resulting tar oil is collected and disposed of. After heating the plastic to a melt, a continuous belt filter and two laser filters deal with remaining impurities before extrusion with hot die-face cutting. The extruder is capable of a nominal output of 1,600 kg per hour. Round plastic strands that exit the pelleting head are cut off to granules by a rotating knife. The granules immediately fall in a subjacent water basin, where they cool down. At the end, they are weighed, subjected to a manual quick check for gas and water content and stored in batches in silos for transport.

Production Line 3

Line 3 was put into operation in 1997, making it the oldest production line on-site. It has the capacity to recycle almost 10,000 tons of input per year. Originally, the set-up was the implementation of a standard plastic recycling concept by Previero. Over time, however, adaptations were made by the plant operator when it comes to drying, extrusion and process water management.

On line 3, the plastic bales are opened manually and then the material is placed by the loader in the pre-loading bunker leading to the bale ripper. The roughly shredded material gets freed from impurities by hand in a sorting cabin. Afterwards, the material gets cut by a shredder of 160 kW, followed by a drum screen with a mesh width of 30 mm, which ensures appropriate particle size for the washing process.

About 25-30 m^3/h are cleaned at the washing section. There, the first process step is a sedimentation tank. It is responsible for the removal of heavy contaminants and easy to remove impurities adhering to the material. Afterwards, the plastic particles are further softened in the washing mill to dissolve the hard to remove impurities from the particle surfaces. A screw press transports the material from the mill to the cleaning centrifuge, where it removes the rest of the now dissolved adhesives. The installed screw press is equipped with a perforated screen with a mesh width of 3 mm and has a power of 18 kW. After the cascade of centrifuges, a radial fan blows the material to the washing silo. The washing silo is designed redundantly. While one silo is loaded, the other is being fed. This results in a continuous process despite batch-wise filling.

The mixture of water and material produced in the washing silo is emptied into the pump basin. There, a stirrer homogenizes the material. Light and slightly less dense particles than water whirl up and pass through a combination of separating basins and centrifuges. The polyethylene-rich accept floats to the surface and is drawn off via paddles. Heavy and more dense material sinks to the ground. At the bottom of the funnel-shaped pump basin, a 45 kW pump feeds the sediment to the hydrocyclone battery, positioned on line 1, to recover remaining valuable material that got dragged along the stream. Any other material ends up in the reject.

The output at the end of the density separation is a polyethylene-rich fraction. A radial fan conveys the material through the drying section of the process, to a heat exchanger unit designed like a silo and a thermal capacity of 160 kW–220 kW. Hot water at 90℃–100℃ heats the process air to 80℃, which then dries the blown by plastic flakes. Finally, the material passes through a storage silo right before the extruder. Here, eventually, additives (virgin material, filter backwash, etc.) are added as needed. At the beginning of the extrusion process, a cutter compactor compresses, homogenises and heats the plastic flakes. Any exhaust gas is sucked-away and quenched. The resulting tar oil is collected and disposed of. After heating the plastic to a melt, two continuous belt filters and a laser filter deal with remaining impurities before extrusion with hot die-face cutting. The extruder is capable of a nominal output of 1.200 kg per hour. The extrusion process itself is the same as in line 1.

Plant Flow Charts

In order to research the inner processes of the recycling plant, an elaborate plant set-up of the process is established to depict processes and the direction of mass flows in a diagram. This STAN Diagram is the foundation for any calculation and mass flow analysis on the plant. Figure 3.4 gives an impression of the plant layout. The dimensions of the system and its representation in a STAN diagram make it necessary to clearly display the individual process steps in another view. Thus, a more detailed depiction of the plant flow charts of line 1 and line 3 can be found in the following section. Their respective plant flow charts are depicted in Figure 3.1, Figure 3.2, and Figure 3.3.

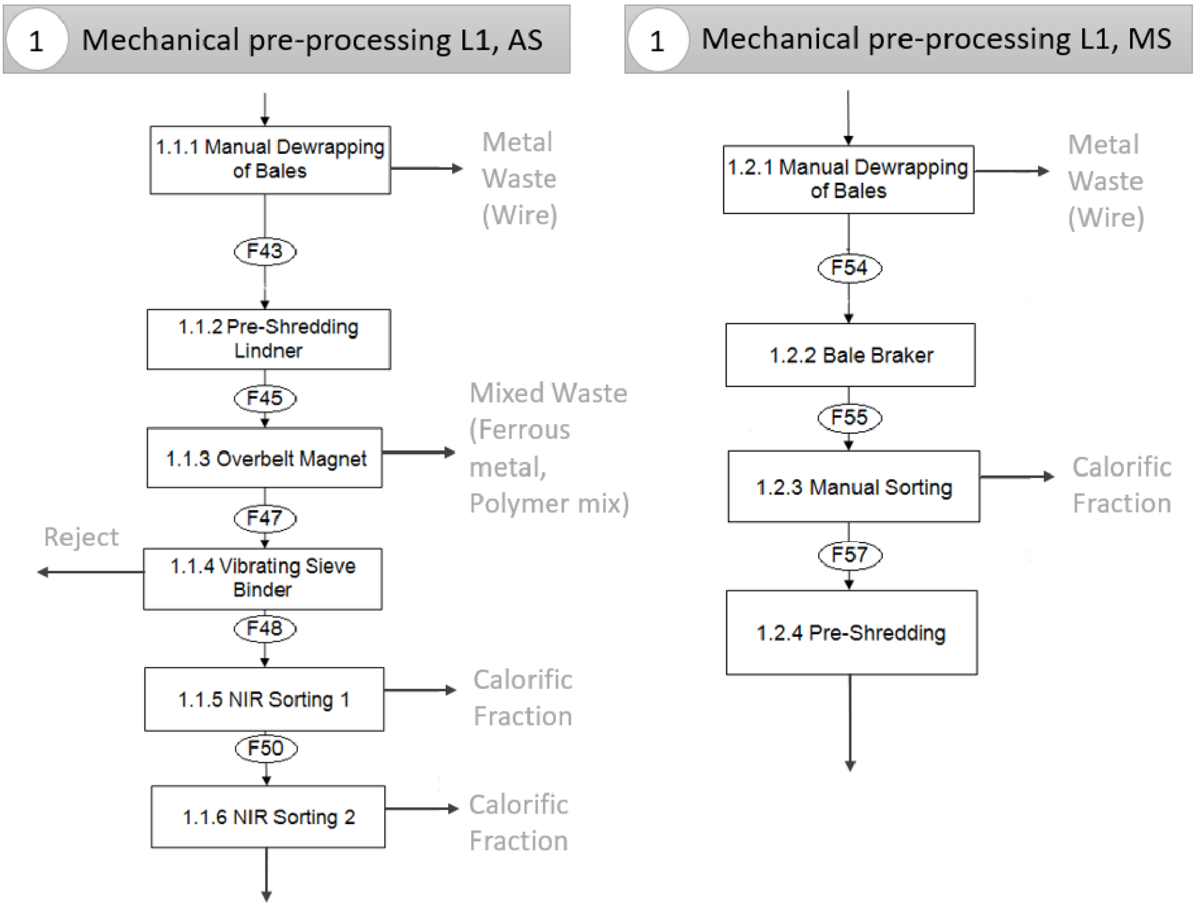


Figure 3.1.: Schematic process flow chart of production line 1 (L1) of the exemplary plastic packaging recycling plant, part one: Mechanical pre-processing with automatic sorting (AS) and mechanical pre-sorting with manual sorting (MS). Figure to be continued on the next page.

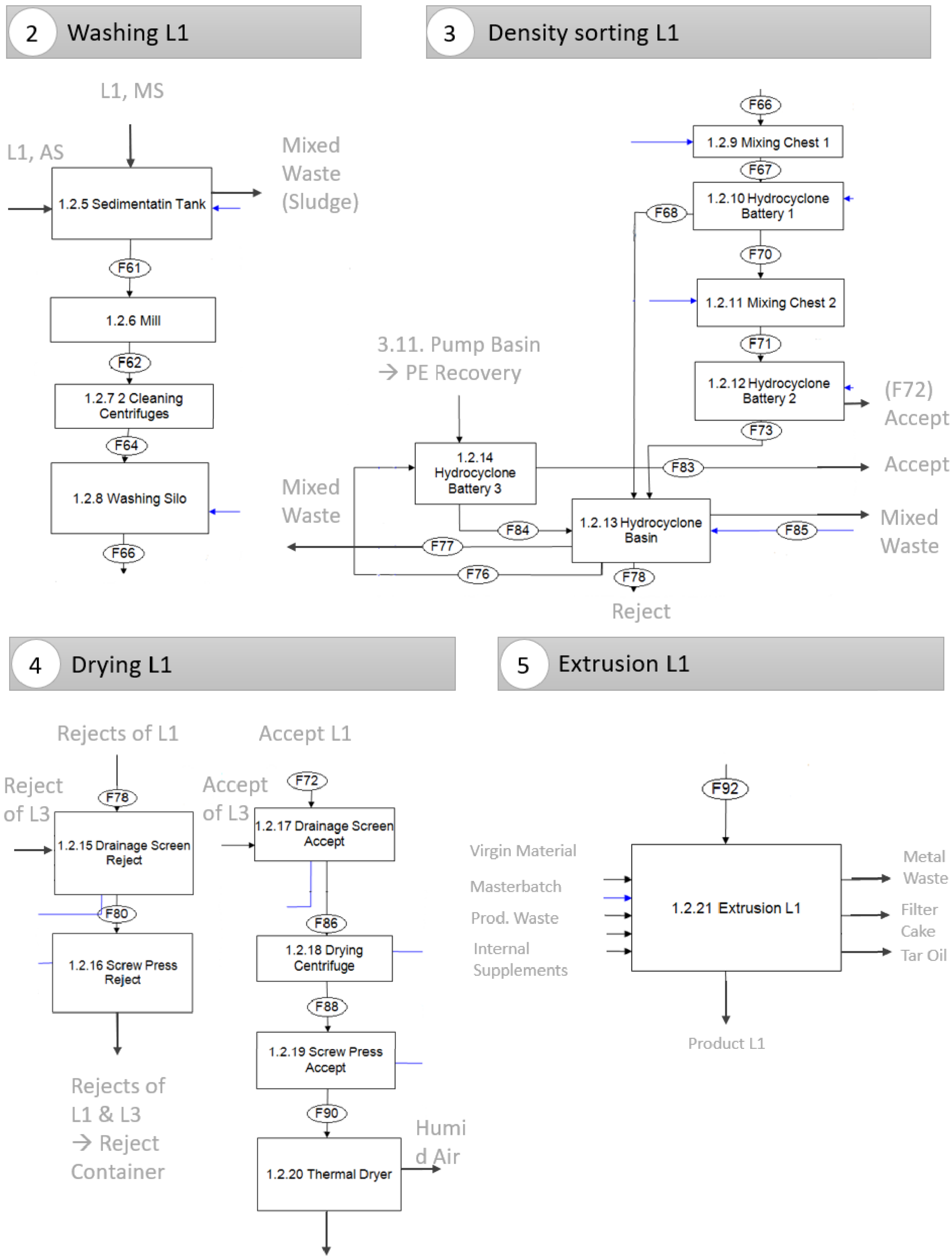


Figure 3.2.: Schematic process flow chart of production line 1 of the exemplary plastic packaging recycling plant, part two

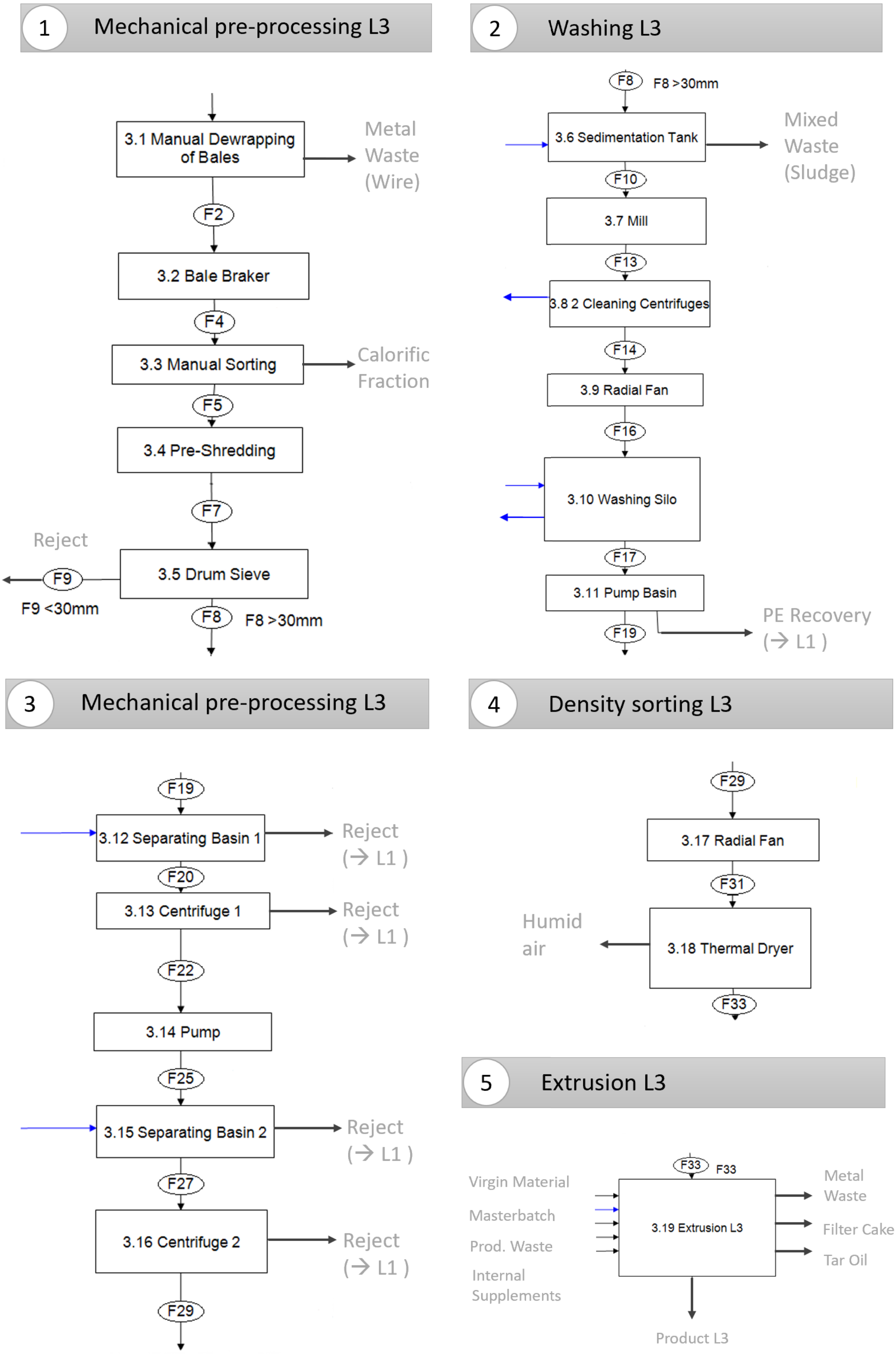


Figure 3.3.: Schematic process flow chart of production line 3 of the exemplary plastic packaging recycling plant.

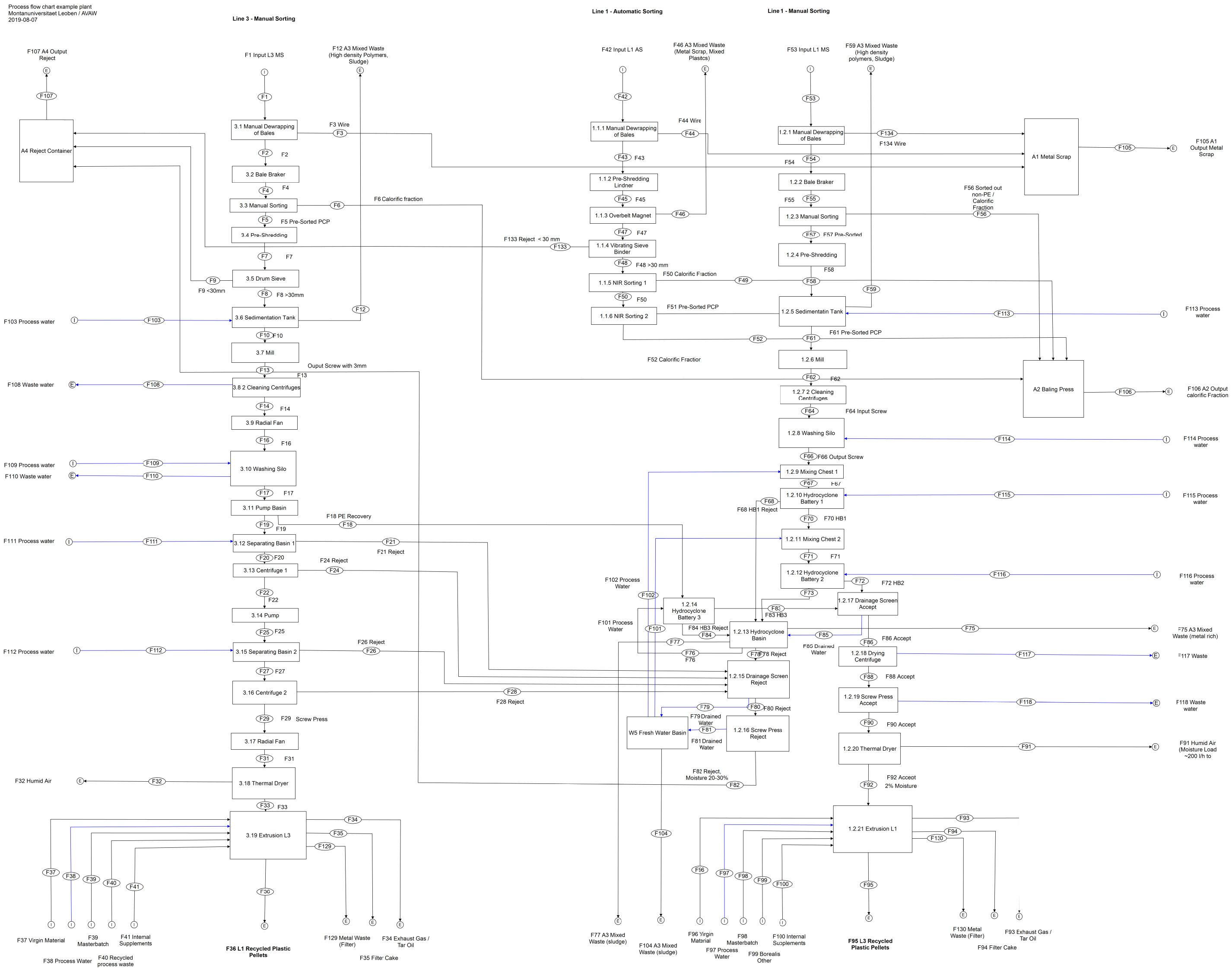


Figure 3.4.: Schematic view of the system setup of line 3 (to the left) and line 1 (to the right) of the exemplary flexible plastic packaging recycling plant.

3.1.2. Material Flow Analysis of a Flexible Plastic Packaging Recycling Plant

The summary of the collected input and output data is shown in the following section. An explanation on the method in use, the assumptions and their limits are to be found in section 2 Material and methods. Table 3.2 shows the result of the input-output balance of all export and import flows with regards tot the system limits. detailed material flow analysis for the recycling plant. Figure 3.5 gives a graphical overview of the evaluated mass flows, clustered by the material groups recycling input, by-products and product output. Finally, Figure 3.8, Figure 3.9, Figure 3.9, Figure 3.8 graphically display the detailed routing of materials flows of the flexible waste plastic packaging recycling process with regards to line 1 and line 3, calculated by the means of MFA.

Input-output Balance

In total, both production lines have a capacity to recycle about 27,500 tons of flexible waste plastic packaging per year and produce up to 18,150 tons of recycled LDPE granulate in 2018, compare to input-output balance presented in Table 3.2.
A quantitative breakdown of the input-output balance subdivided in categories and production lines is shown in Figure 3.5. Most common input (71 %) of the recycling plant is input category 422, which represents printed on colourful LDPE foils. In general, the input is provided by the national company ARA and suppliers of the adjacent nationalities, Germany (Alba) and Italy (Corepla). Most input, 65 % - 17,913 tons - of the total annual input is recycled by line 1, producing 58 % - 10,500 tons - of all product output, Being equipped with less modern machinery results in lower throughput of line 3, coping with 35 % or 9,533 tons of the total plant input to produce 42 % or 7,673 tons of product output. The automatic sorting lane of line 1 is typically fed with input category 422 and 429. Since line 3 only relies on manual sorting attention is paid to feeding input that is more likely to be clean like category 421, consequently output product LDPE translucent is mainly produced by process line 3. Overall, the three categories LDPE coloured, LDPE translucent, and LDPE black contribute up to more than three quarters to the plant output products. The lion share is taken by a single product type, LDPE coloured with 59 %. The rest consists of light coloured LDPE and smaller batches of LDPE black (+2 % black) and LDPE natural. Please note that LDPE black is subdivided in plastic granules designated for foil and pipe production. The calorific fraction is the principal by-product with a share of 53 w-% to all by-products. Second comes reject, contributing 31 w-%. The specific share of by-products is given in part (h) of Figure 3.5. According to the figures, the input of process line 3 ejects a significant lower number of contaminants during the process.

Key Performance indicators

Considering the overall recycling plant, PR results to 63 % and RE equals 66 %. PR for line 1 results to 56 % and RE equals 60 %. PR for line 3 results to 75 % and RE equals 78 %. The low value for PR of line 1 indicates high throughput with low output rate. This implies, that a significant amount of non-PE material consumes valuable machine capacity and energy of the recycling plant without contributing to the share of products. Additionally, RE for line 1 also indicates mediocre plant performance. To elaborate an example, the most common input of line 1 is Number 422 "LDPE foils coloured, printed on". According to the definition listed in Table 2.1, contamination of "LDPE coloured, printed on" is tolerated up to a maximum of 10 w-% caused by transparent packaging and fertilizer bags. Assuming, hypothetically, that this margin is fully utilised, it still indicates a significant surplus of the claimed share of pollutants mixed in with the coloured LDPE foils since an PR of 56 % means in reverse 44 % of input material is lost during the process. The specific share of by-products is given in Table 3.3. For each ton of input at line 1, 407 kg of non-PE material is ejected in the course of the process. For line 3, the figure is 227 kg. According to the personnel, on average 10-40 % contraries

Table 3.2.: Summary of the mass flow analysis of the recycling plant in tons per year, 2018.

Category [-]	**Material** [t/a]	**Line 1** [t/a]	**Line 3** [t/a]	**Total** [t/a]
Input plastic waste	421	1080	4610	5690
	422	14 965	4460	19 425
	423	1	55	56
	429	1846	286	2132
	Other	21	142	163
		17 913	9533	27 466
Input other	Virgin material	253	473	726
	Masterbatch	80	5	85
	Industrial waste	298	111	409
	Internal recycling	154	77	231
		785	666	1451
Output by-products	Metal waste	62	46	175*
	Mixed waste	51	11	1175*
	Reject	2412	547	2959
	Calorific fraction	3696	1279	5175
	Sludge	224	38	1644*
	Tar oil	1	1	2
	Filter cake	839	243	1081
		7285	2164	12 211
Output products	LDPE natural	0	246	246
	LDPE translucent	183	2443	2625
	LDPE coloured	7473	3168	10 640
	LDPE light coloured	163	1666	1829
	LDPE black (+0%)	902	86	988
	LDPE black (+2%)	1752	57	1808
	Other	2	8	10
		10 474	7673	18 147

*Deviation to subtotal is due to non-assignable amounts of waste to L1 or L3

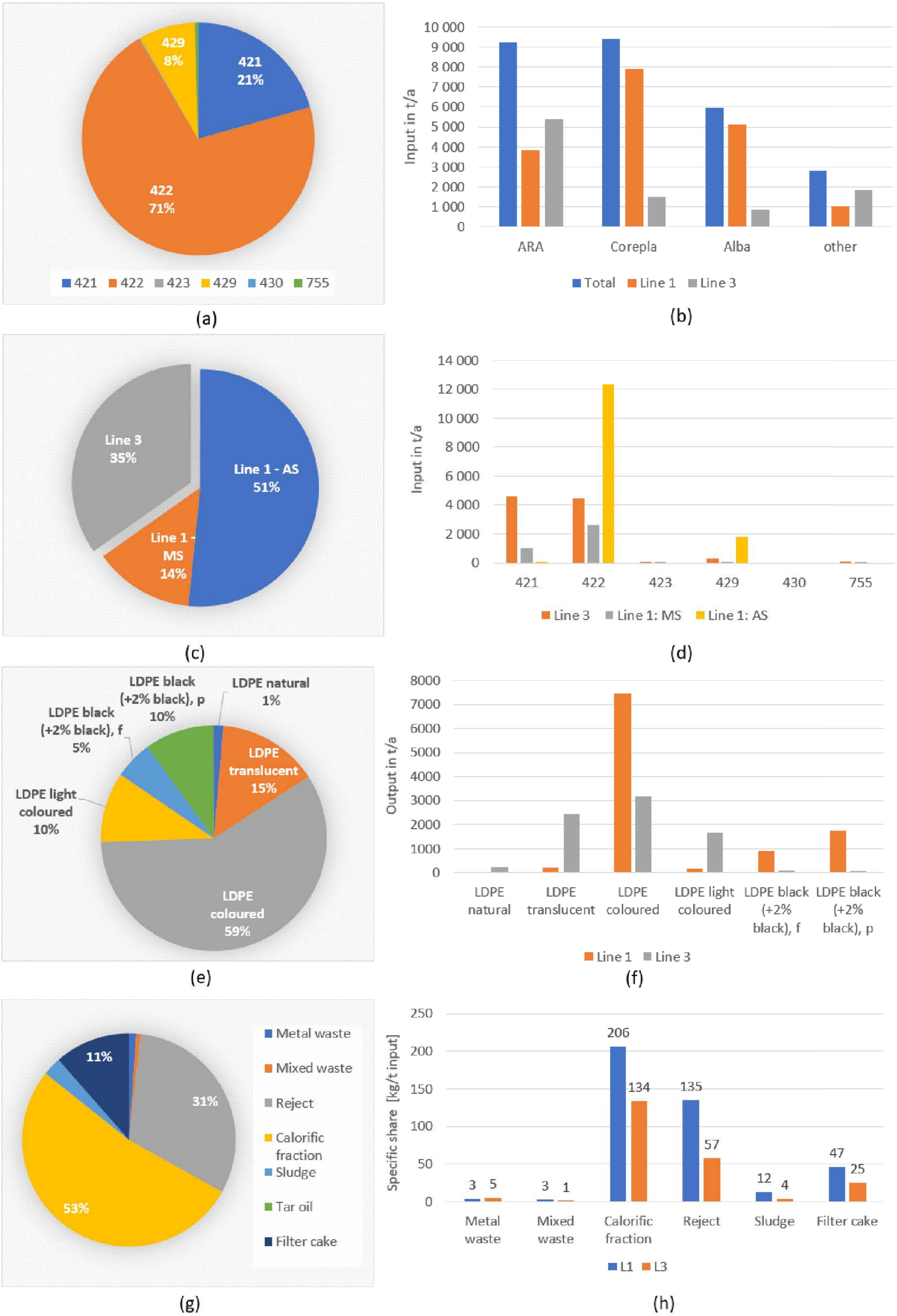


Figure 3.5.: Input-Output analysis of the plastic recycling plant. (a) Overview of total plant input. (b) Supplier of plant input. (c) Input for line 1 manual sorting (MS), line 1 automatic sorting (AS), and line 3. (d) Input according to category and process line. (e) Product output of the plastic recycling plant. (f) Product output per process line. (g) Composition of by-products. (h) Specific share of by-products per process line.

Table 3.3.: List of by-products and their specific share on input in 2018.

By-product [-]	**Total** [t/a]	**Total** [%]	**Line 1** [t/a]	**Line 3** [t/a]	**Share** [kg/t input L1]	**Share** [kg/t input L3]
Metal waste	175	1	62	46	3	5
Mixed waste	1175	10	51	11	3	1
Calorific fraction	2959	24	2412	547	206	134
Reject	5175	42	3696	1279	135	57
Sludge	1644	13	224	38	12	4
Tar oil	2	0.1	1	1	0	0
Filter cake	1081	9	839	243	47	25
Total non-PE	12 211	100	7285	2164	407	227

are part of the input stream. This perception corresponds to the current findings, whereby the share of contaminants actually seems to be in the upper percentage range. Almost half of the input material does not go through the process to the end. For each line, the main share of by-products is taken by the calorific fraction and the reject, both are characterized by high plastic contents. Those two are responsible for more than three quarters of all by-products. At line 1 341 kg of plastic (calorific fraction plus reject) gets discarded by the process. This accounts for 83,8 % of all by products at this line. At line 3 191 kg of plastic (calorific fraction plus reject) gets discarded by the process, which reflects 83 % of all by-products of line 3. Since no experiments were conducted on material composition, the mass flow analysis was only elaborated on an overview level. Therefore, it cannot give any further information on sorting efficiency. But multiple ways on how to influence the sorting efficiency of a NIR-sorting system can be named, though. A bad sorting efficiency can be caused by overloaded belt conveyors, wrong identification, or no identification at all. All of which are in direct negative correlation with the downstream product quality and material properties.
This high value of by-products can have two possible reasons. First, it might be an issue of poor quality at delivery. Hence, a significant amount of input is legitimately rejected in the sorting section for being non-PE material from the start. Second, it might be an issue of bad sorting efficiency. Hence, a lot of valuable PE plastic material that enters the recycling process is lost along the way. Both arguments are worth investigating and are recommended to be subject to further research. Since no composition analyses of the input material are available, it is not possible to say exactly whether the former or the latter applies. The subjective perception of the plant personnel tends rather to the former, but on the other hand they pointed out that the PE content of the input material decreases continually. They highlighted, that a lot of machinery is at their limit of maximum capacity e.g. NIR-sorting cascade. So either argumentation might be true to some extent. One way or the other, the product quality suffers as a result.

Transfer coefficients

The extensive calculation of transfer coefficients were done according to the principles of mass flow analysis. For detailed results the reader is guided to the Appendix A of this thesis.

Graphical Results of the MFA

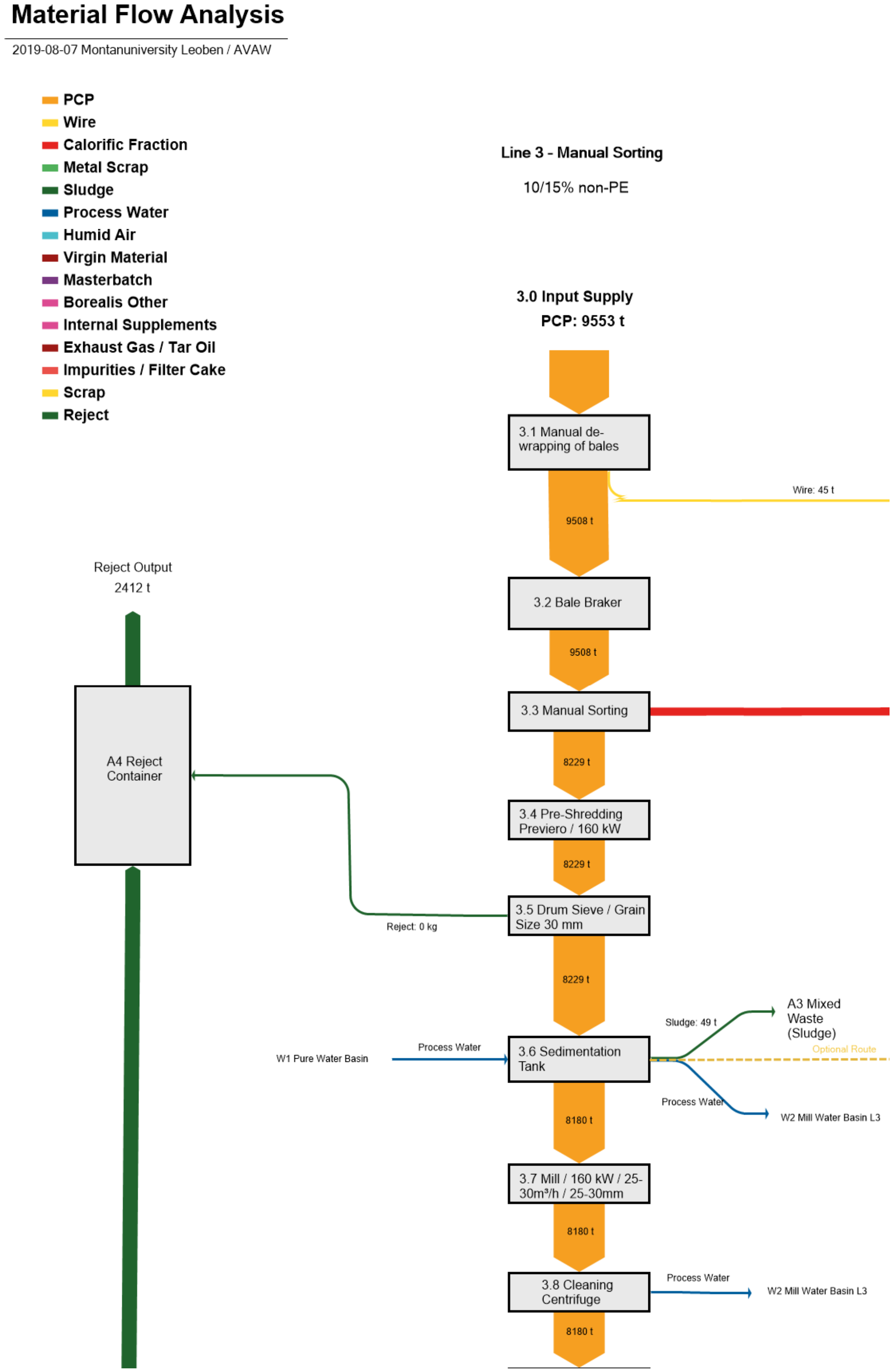


Figure 3.6.: Sankey diagram of the detailed result of the MFA of the exemplary plant data for line 3 of 2018 using the free software eSANKEY. Part 1.

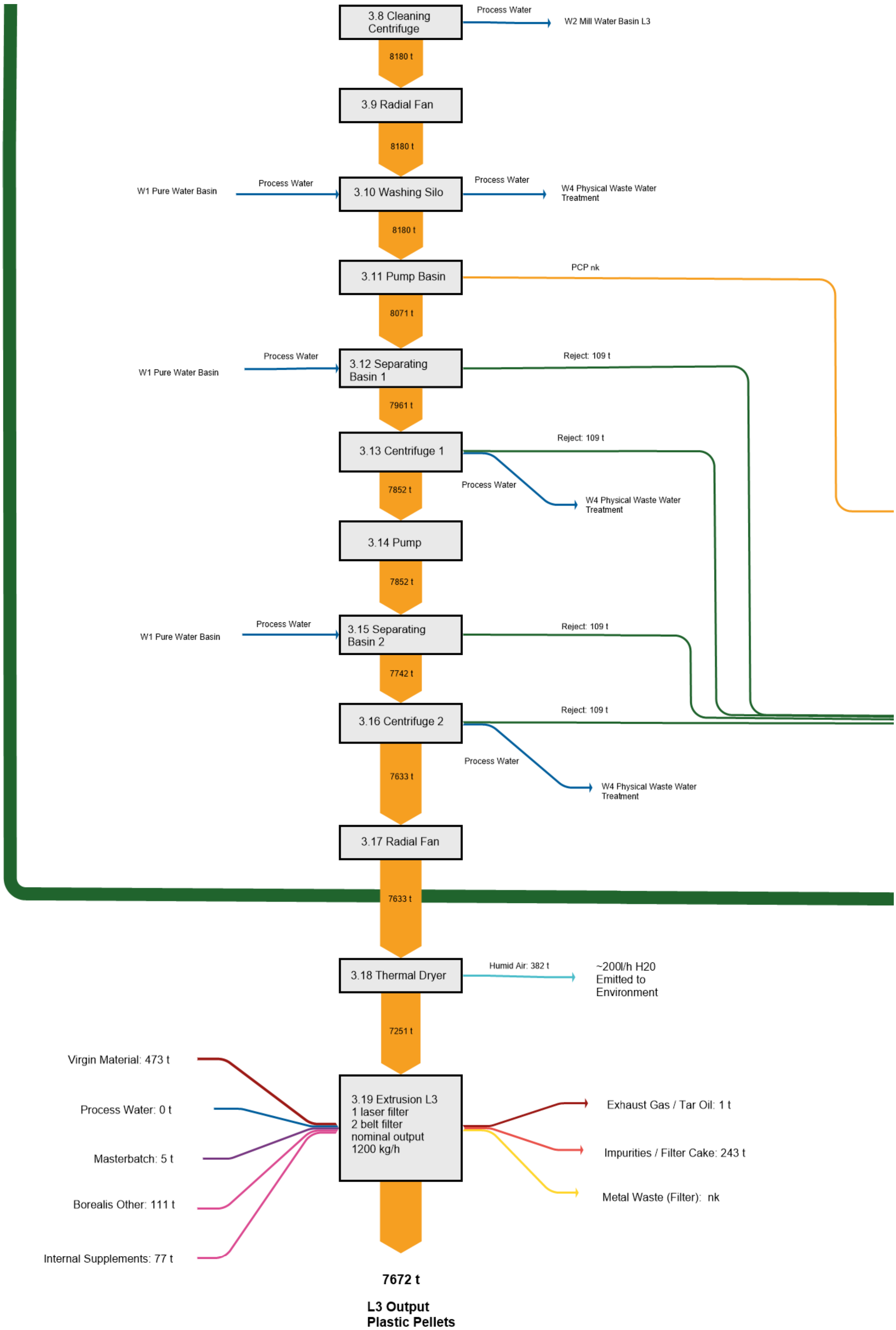


Figure 3.7.: Sankey diagram of the detailed result of the MFA of the exemplary plant data for line 3 of 2018 using the free software eSANKEY. Part 2.

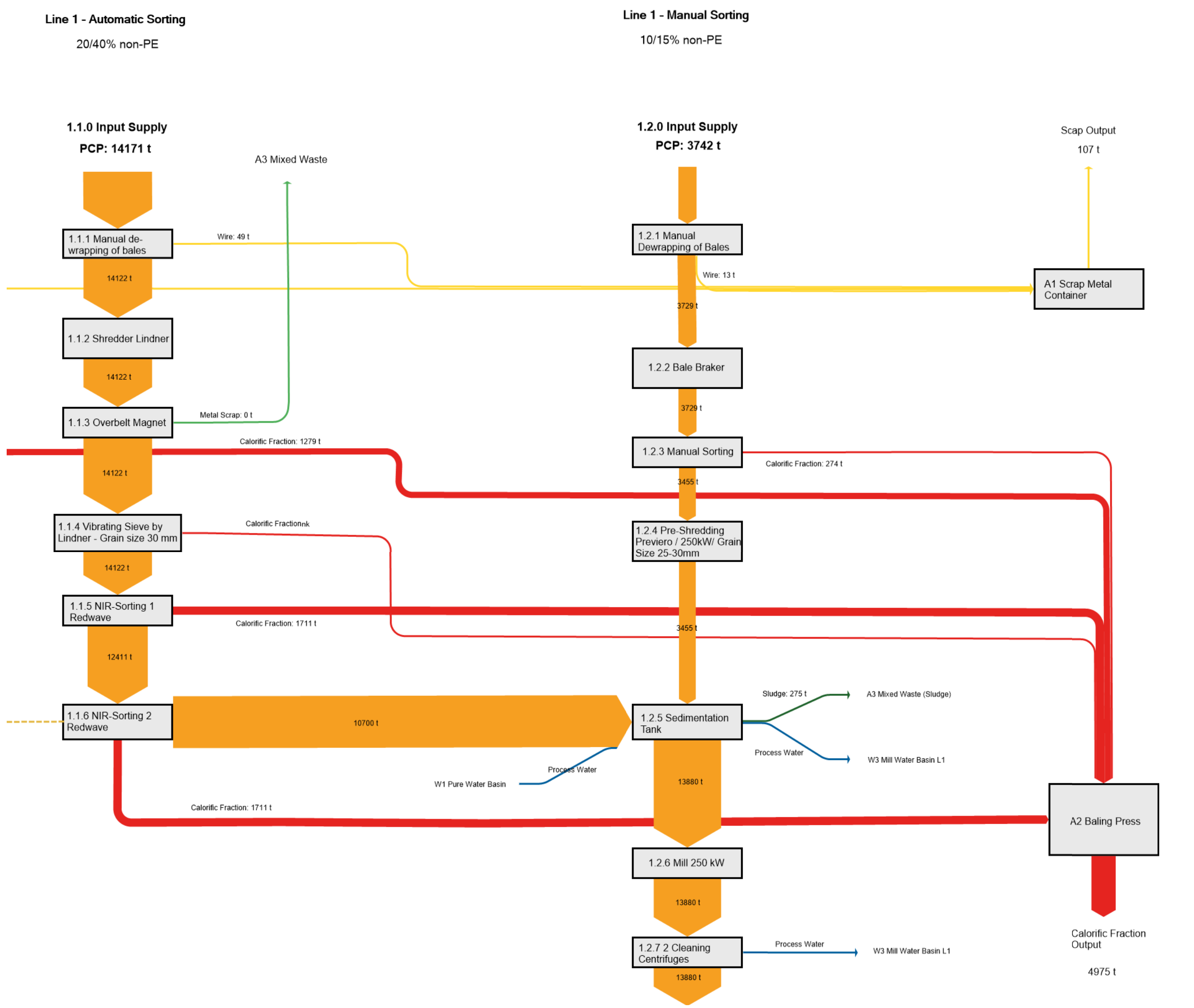


Figure 3.8.: Sankey diagram of the detailed result of the MFA of the exemplary plant data for line 1 of 2018 using the free software eSANKEY. Part 1.

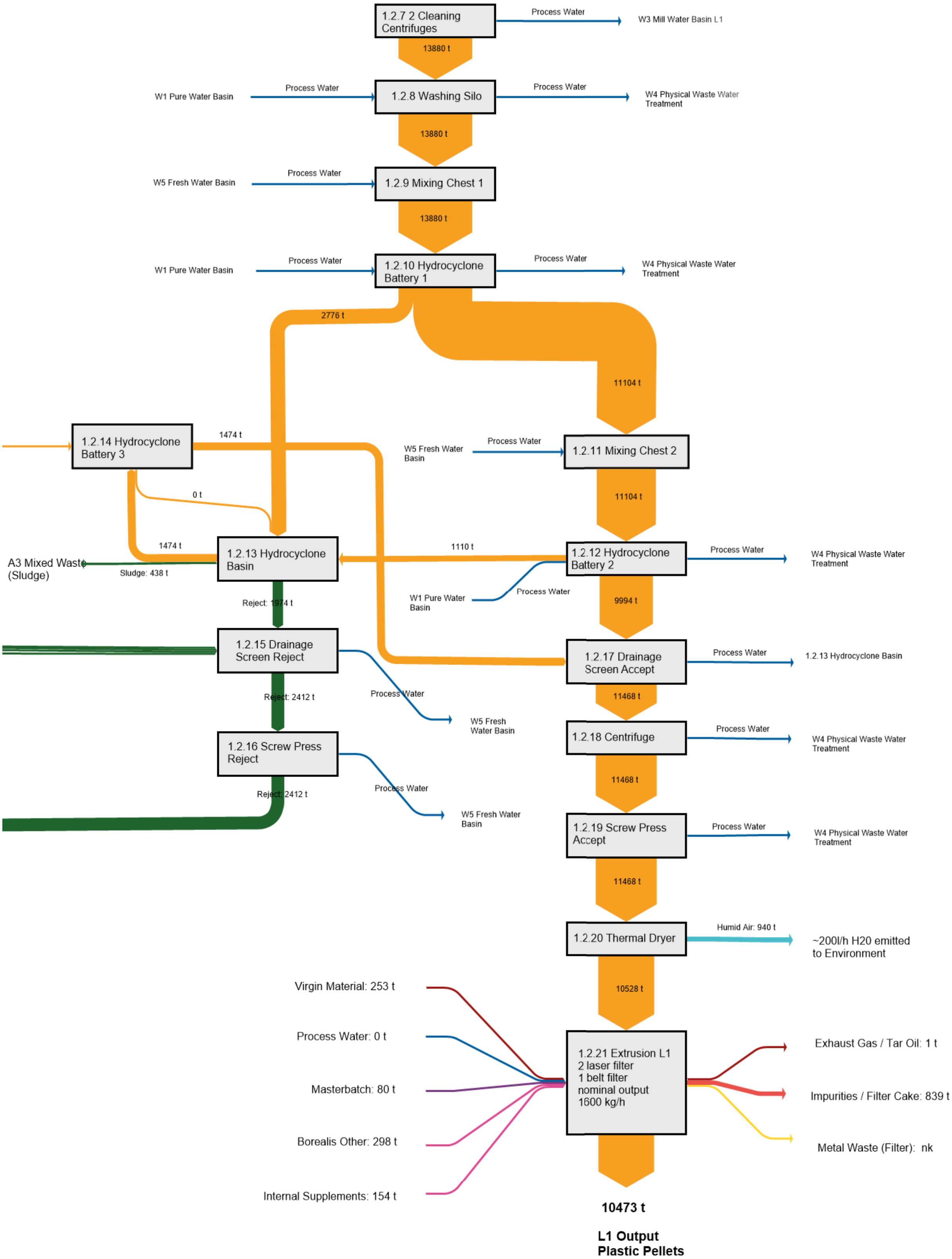


Figure 3.9.: Sankey diagram of the detailed result of the MFA of the exemplary plant data for line 1 of 2018 using the free software eSANKEY. Part 2.

3.1.3. Challenges as seen by the Stakeholders of the Exemplary Recycling Plant

This section summarizes the interviews and feedback of the staff of the exemplary flexible plastic packaging recycling plant. Overall, every later on discussed challenge is partially an aspect of one or more of the four fundamental rules of recycling according to Pomberger 2021.

1. What is not collected, cannot be recycled.
2. What is not in it, cannot be taken out.
3. What is not identified, cannot be sorted.
4. Without a market, there is no demand.

Feedstock The handling of films and foils is a challenging task. They are thin, light-weight, of low density and cause a voluminous material flow, that challenges machinery when it comes to conveying, sorting or feeding, since it tends to flutter off the conveyor systems. Next to physical properties, the recycling of flexible plastic packaging has a strong dependency on the composition of the feedstock. Recycling companies must cope with dirty feedstock material. To prepare for even less clean material is advisable, because the attitude to separate waste seems to decrease in the younger generation (VOEB 2021). In addition, modern packaging design generates an increase of material composites and diversity of materials used for packaging. One product was pointed out to be highly problematic due to false detection at the sorting section and increasing shares of the plastic waste input stream: multilayered films because they are hard to detect, identify and sort. Although flakes are correctly detected as PE by the NIR sensor system, their multiple layer composition can consist of a combination of PE and various other material in the mid-layers, which from experience have a negative influence on quality. Up to now, neither the sorting crew nor the NIR sensor system can distinguish whether the film at hand consists of a structure like PE-X-PE or if it is made of PE monomaterial. Finally, undesired material ends up in the product stream causing streaks, specks and gels due to incompatibility with the PE melt. With regards to discussions on site with the plant and quality manager, the following list of contaminants and candidates for gels is established. It ranks the materials according to their negative impact on product quality. The materials identified to have the worst effect are

- PVC,
- PA,
- Elastomers e.g. rubber, latex,
- PP,
  - <1 % for LDPE natural, translucent, light coloured
  - <5 % for LDPE coloured and black
- PET,
- Fat, oil, detergents or other chemicals,
- Organics e.g. wood, paper

And tolerated in not too high quantities are

- LLDPE,
- HDPE,
  - for LDPE natural, translucent, light coloured, and
- Inert material.

A combination of laser and band filters remove residing non-PE particles larger than 100 micrometres from the melt. Nonetheless, a significant share of pigments remains, which typically leads to a distinctive greyish, brownish hue of the recycled LDPE granulate. Small amounts of black masterbatch (<2 %) are added to the plastic melt to avoid the grey hue and get a product in full black. At the exemplary plant, roughly 84 % of all products are either coloured or black. Ecodesign can be a viable tool to increase the recycling of multilayer films. A more environmentally friendly design with removable or self detaching parts when shredded consisting of monomaterial, or fewer different types of materials, can have a consistently positive impact on the subsequent recycling chain.

Personnel The plant depends on its operators and their expert know how. They are the key to the optimal utilization rate, influence to a significant degree the quality of the produced recycled LDPE granulate and are responsible for continuous quality assessment. For example the experience of the team at the manual sorting cabin on differing various materials or the driver of the hauler and its influence on the load of the feeder belt. The more continuous the loading, the better the distribution of material on it and the better is the sorting efficiency of the downstream NIR sorting cascade. However, the recycling industry does not attract skilled workers. To invest in regular training of all employees is of the essence to ensure high quality standards. Last resort is the investment in a higher degree of automation, to promote independence of lack of personnel.

Plant Set-up A challenge concerning the plant set-up is the review and fine tuning of plant processes and existing infrastructure to reduce bottle necks and increase efficiency. But with the increase of volume and composite design of flexible plastic packaging, throughput and mechanical recycling is soon at its limits, which leads to diminished product quality. This circumstance demands a higher degree of automation and adaption to new recycling technologies to maintain the current extent of recycling efficiency, which is related to a significant increase in operational an capital expenditures, though. Typical pain points are sorting, extrusion and washing in combination with waste water treatment, but it is strongly recommended to upgrade and innovate. There is no answer to the question if a lot of valuable PE plastic material is either lost at certain process steps, or legitimately rejected for being non-PE material from the start.
For example, a revision of consisting legacy NIR sorting system can have a positive effect. Old NIR sorting systems often still have legacy software running, dating back to time of their commissioning. With an update of the internal data base and material library, one can broaden the scope of the NIR application. This can enable additional detection of troublesome impurities. For example, plastic bags such as organic waste bags made of polylactid acid (PLA) cannot be identified, since they are too new to be represented in the material library. It is unknown how the present sensor system reacts to such objects. In the worst case, they remain in the product stream and interact negatively with the product material. Also, modification of the NIR sorting set-up to a combination of a rougher, cleaner, and scavenger is bound to additionally enhance purity of the LDPE product but there is a lack of space on the plant site to do so. Improvements of the legacy set-up and its direct environment, such as the load of the feeder belt and the belt itself, are preferred and also have potential to improve the sorting success. Recent sorting issues are: Up to now, if piles of foil stack onto each other only the first layer of material is scanned by the NIR sensor system since it uses reflectance mode. Thus, only the upper material is assessed and evaluated by the sorting algorithm. This is of great importance for identification, selectivity and yield. A positive sorting signal results in the false positive ejection of multiple objects. The other way around, a negative sorting signal may remove valuable objects from the product stream together with the undesired object For the recycling product, everything that is not PE or falsely identified as such is considered problematic, since it can disturb the downstream extrusion process. Coated, high pigmented or carbon black objects and multilayered films are very bothersome in this case. Many carbon black objects absorb near-infrared radiation leading to no evaluable NIR spectrum at all or to a distorted spectrum similar enough to another material which can result in false positive characterization. Another possibility is that the material has not been taught to the NIR system. Consequently, no identifi-

cation can take place, or it is wrongly assigned to a known material with similar NIR properties. The material is then randomly ejected either into one or the other material stream. Concerning multilayer films, the upmost layer might consist of PE, but, again, a NIR sensor system is only able to scan the surface of an object, having a penetration depth of a couple millimetres, see section NIRS. Some or multiple layers may be made of unfavorable materials for the recycling process, causing trouble in the extrusion process, as they get dragged along the accepted material stream until they are incorporated in the plastic melt regardless of the polymer. Installing an upstream separator for ferrous and non-ferrous metals also boosts the level of product purity. In addition, it reduces wear and prolongs equipment service life of e.g. pumps, as these small pieces of metal form a material-water mixture, which is highly abrasive. The implementation of colour sorting of the feedstock is thought to enable a broad range of new applications.
When it comes to plastic recycling, the extrusion step is of utmost importance. It is responsible for homogeneity, degassing, and filtration of the plastic melt and is in direct correlation with mechanical properties. The better the mixing, the better the product. On the other side, extrusion can also have negative side effects e.g. dead zones along the extrusion screw can cause degradation of the melt, which results in gels (Spalding et al. 2018, p. 10).
Another notable challenge is the improvement of the process water quality. The washing step is responsible to soften the plastic flakes with increasing temperature and remove any adhering fines. As feedstock gets more and more unclean, more and more contraries need to be removed by the washing section. Consequently, washed out impurities are dragged along with the process water. Process water is recirculated multiple times before it is led to the sewage plant. Some aggregates at the washing section were not designed to cope with such highly polluted material. This results in residues of waste sludge at inaccessible places, which must now be removed by hand. Research on the waste water treatment can lead to a reduction on sludge sediment and finally to an improved washing process with less contaminated process water. Besides antispumin to diminish the foam, detergents can be useful during the washing process. They not only drag along residues but may also reduce unpleasant smell of products made of the recycled LDPE. It has to be pointed out, that this could be a pointless effort, because odour often roots in the composition of the polymer itself, so washing has no effect on that characteristic. Although research on the existing washing compounding process might help.

Quality Assessment Quality assessment is the main factor to create deeper insights on plant operation, master its processes and ensure compliance with standards and regulations. The identification of the key metrics for plant performance and product quality need to be assessed whether they are helpful, correct, accurate or even possible. It is recommended to do a critical review of the internal quality control - are the examined criteria sufficient for the chosen standard? Plastics are always designer materials that underlay constant change. Sometimes the detection or quantification of a material is not feasible with existing technologies and new methods must first be developed. Until then, the process is prone to possible effects of alien material on operation or products e.g. multilayer films. Another challenge is the equipment of the quality laboratory. Depending on the degree of automation and place of installation (off-line or on-line), it is more or less costly, needs space in the plant set-up, regular maintenance and trained personnel to interpret the results. With a low degree of automation, quality assessment is only possible up-front or at the back end of the recycling process, since recycling equipment often operates in an enclosed environment, where material is inaccessible for inspection sampling done by hand. The less quality assessment is automated, the more time consuming is testing. With restricted time, the range of tests and the sampling size diminishes. The worst case scenario is total system failure resulting in an uncontrolled and unstable process, that leads to random material properties of the product, which renders any product useless for any further downstream processing. Although online sensor based quality monitoring is expensive, the investment pays off, as product margins and quality do increase. Another point is that quality reporting must be taken seriously and has to result into action. In the best case, the quality manager is equipped with competences and has enough authority to enforce quality related measures, backed up with fundamental knowledge on plastics, supplemented with repeated training and understanding by the co-workers.

By-products The recycling of post-consumer plastic waste generates, besides the produced recycled PE granulate, a significant number of by-products. By-products are often valuable material, which contribute to the profit of the recycling plant and have an intense interrelationship with product quality. With a share of 20.6 % per tonne of input of line 1 and a contribution of 53 % to all by-products, the calorific fraction is by far the most prevalent by-product. It holds therefore the greatest potential to optimize plant operation. The majority originates at the NIR sorting step. Despite their significant share and LDPE potential, they are used as subsidiary fuel in co-incineration plants. They are in high demand for this use until a certain threshold of chlorine is exceeded. If the contamination with chlorine is too high, the incineration plant has problems to comply with emission regulations and faces corrosive attack by hydrochloric acid on plant equipment. Thus, the recycling company is charged with a gate fee for compensation instead of creating revenue by providing valuable fuel. Therefore, larger volumes of low grade material increase costs for disposal, cause low grade by-products and generate less material to be processed into valuable products. Which then again has a negative impact on the total recycling quote. If not managed wisely, their possible positive economic effects are not only diminished, but turned into a massive cost factor. Larger volumes of low grade material lead to increasing costs for disposal by contractors and less material to process to valuable products. Additionally, uncontrolled and unstable processes lead to varying material properties of the product. Without any intervention, the worst case scenario is a total system failure, which can render the product useless for any further downstream processing. It is therefore appropriate to pay special attention to by-products, as they are a key factor for successful recycling.

Market The secondary raw material market is very competitive . Therefore, recycling companies are highly dependent on contractors and suppliers when it comes to feedstock quality. Long-term contracts and limited number of feedstock suppliers bare little basis for negotiation or to exert pressure if material does not comply with the data sheet. When a complaint is filed, the recycling company needs solid proof for its claims. Providing it, is personnel intense and time consuming because it can only be determined by extensive bale sampling coupled with a thorough supplier evaluation, however it is customary in the industry that complaints are only possible within 24 hours upon receiving material. This measure is used very rarely and only in extreme emergencies in order to maintain good business relations with the suppliers. Monetary revenues range from 60-80 Euro for the processing of already very clean material up to about 400 Euro for the recycling of very unclean plastic packaging material. Most popular are clean, translucent, white or natural waste LDPE flakes. Demand drives up the price of this raw material accordingly. In addition, prices strongly correlate with the fossil fuel market. Cheap petroleum-based input materials lead to a cheap production of virgin plastics, which erases possible price advantages of secondary commodities over primary ones, leading to lower demand. A market for by-products must be found as well, as they have significant influence on revenue and the profit per one ton of LDPE. If not handled properly, the estimated profit per ton can quickly be diminished or turn into loss. Besides these market related challenges, the recycling company must operate in the waste management regime. In this field, special legal conditions apply, that make it hard for a company to produce something that is able to leave the waste management regime and get the legal status of a product, that, nonetheless, has to compete with virgin material. The products are often handicapped with inferior optical and mechanical properties. Concerning pigments, only 16 % of products, LDPE translucent and LDPE natural, are currently without colouring. Contractors prefer to buy uncoloured and clear products to have the full range of applications and product colouring for their customers at hand. If this is not possible, full colours are preferred over the psychologically negatively associated greyish, brownish colour. Adding black masterbatch works as a short-term solution, whereby it does not change the need for any sort of colour control of the LDPE granules. Hence, they are disqualified for many profitable applications. Furthermore, these materials suffer from a psychological disadvantage. Promoting the use of recycling material for a product doesn't give all customers the same incentive to buy. The knowledge of buying an eco-friendly product is only important to customers with a significant pro-environmental attitude. For customers with less eco-friendly preference, other attributes such as price and quality are more likely to influence consumer behavior (Borin, Lindsey Mullikin, and Krishnan 2013, p. 124). As a consequence, products made of secondary plastic material are often considered to be too "green" to be good. Which sums up to the challenge to manufacture goods made of recycling material of a quality which at least is comparable to new products (Borin, Lindsey Mullikin, and Krishnan 2013; Dropulić and Krupka 2020; Kabel, Elg, and Sundin 2021). Currently, the main products manufactured from recycled LDPE are garbage bags and foils for agricultural or constructional use. To recycle flexible plastic waste to an extent, that it can be seen as a viable player on the raw material market, and as feedstock for highly valuable products, is expensive. An economic break-even point is not necessarily reached when operating. Since the recycling of flexible plastic packaging is part of the public interest, subsidiaries can be an effective measure to buffer the costs and promote the recycling to more sophisticated products. Up to now, a lack of clarity often exists about the desired quality due to uncertainty to which application the produced LDPE recycling lentils should be aimed at. Recycling costs are proportional to recycling effort, therefore, it is economically not sensible to demand the best quality of LDPE granulate. Thus, it is recommended to clarify the application, then choose fitting technical standards, as product requirements can be very application-specific.

3.2. Assessment of Recycling Potential

The goal of this section is to find the answer to research question 2 and 3.

2. "Which share of the yellow bag is contributed by multilayer films and in which product groups do what kind of multilayer films accumulate?"

3. "How could the recycling of multilayer films contribute to a circular economy?"

3.2.1. Hand Sorting Analysis of a 2D Fraction from an Lightweight Packaging Sorting Plant

Prior to the hand sorting analysis, the provided sample of 30.3 kg of waste plastic packaging waste is pre-sorted to separate the flexible, flat and two dimensional waste plastic packaging films from bulky and rigid three dimensional objects, see Figure 3.10.
The remaining sample of flexible waste plastic packaging has a total weight of 10.4 kg, which represents an overall share on the yellow bag sample of 26 w-%. This statement is supported by thee PhD thesis published by Van Eygen 2018, which states the 2D content of the yellow bag, described under the category "Small films" of the separate waste collection (SWC), to be about 30 %.
In numbers, the top product streams, according to category 1, are primary food packaging (n=468, 56 %), followed by primary product packaging (n=155, 18 %). When it comes to weight, the numbers turn. Then, primary product packaging (m=3,323 g, 32 w-%) outweighs primary food packaging (m=2,816 g, 27 w-%) by 5 %. Object-correlated, the five most common goods are household packaging (14 %), bakery related products (10 %), bags (9 %), meat packaging (8 %) and packaging from fresh produce (8 %). Ranked by weight, bags (15 w-%), construction and workshop packaging (13 w-%), mail order pouches from online trading

Figure 3.10.: Exemplary manually pre-sorted bulky three dimensional waste plastic packaging objects excluded from the study.

(12 w-%), the extra wrapping of beverage six-packs (5.7 w-%) and packaging of meat (5.5 w-%) dominate the first five positions. The last five product groups are low in numbers, but high in weight. This might indicate increased use of material (thickness) or the prevalence of PP in them. The following Figures, Table 3.4, Table 3.5, Figure 3.11, and Figure 3.12 summarize the results. A comprehensive list with information on every examined piece of 2D yellow bag material can be found in the appendix B.

Assessment of Recycling Labels According to this evaluation, only 30 % (n=99) of 329 inspected objects have proper marking on them. In total, 70 % (n=230) lack a label for plastic packaging, however, at least the typical green coloured recycling arrow is present at one third it. Plastic packaging consisting of different plastic resins or multiple layers of plastic are hardly ever indicated, since the standardized labels for plastic resins for multimaterial packaging only cover combinations with paper or aluminium. Certain product groups are more likely to be without recycling labelling. These include above all generic plastic bags, packaging for fresh produce and fruit, bakery related packaging, especially packaging to go, and inner layers of dry food packaging e.g. cereal. In general, the product groups to be most likely labeled are industrially processed food and packaging of non-food products.

Table 3.4.: Object distribution matrix of the yellow bag sample. Total n=842.

Category	Primary food	Secondary food	Primary product	Secondary product	Bags	Foils	Total
Bakery products	80	0	0	0	0	0	10%
Meat	70	0	0	0	0	0	8%
Household packaging	115	0	0	0	0	0	14%
Dairy	18	0	0	0	0	0	2%
Coffee	5	0	0	0	0	0	1%
Fresh produce	67	0	0	0	0	0	8%
Snack metallised	32	0	0	0	0	0	4%
Snack uncoated	21	0	0	0	0	0	2%
Frozen food / convenience	38	0	0	0	0	0	5%
Dry food	24	0	0	0	0	0	3%
Beverages / extra wrapping	0	38	0	0	0	0	5%
Construction / workshop	0	0	29	0	0	0	3%
Garden	0	0	0	0	0	0	0%
Household products	0	0	35	0	0	0	4%
Sanitary products	0	0	27	0	0	0	3%
Toys	0	0	47	0	0	0	6%
Wet pet food	0	0	11	0	0	0	1%
Dry pet food	0	0	6	0	0	0	1%
Gift wrapping	0	0	0	6	0	0	1%
Mail order	0	0	0	46	0	0	5%
Wrapping	0	0	0	1	0	0	0%
Carrier bags	0	0	0	0	22	0	3%
Bags	0	0	0	0	75	0	9%
Foils	0	0	0	0	0	29	3%
Total	**470**	**38**	**155**	**53**	**97**	**29**	**842**
Share	**56%**	**5%**	**18%**	**6%**	**12%**	**3%**	**100%**

Table 3.5.: Mass distribution matrix of the yellow bag sample in grams. Total m=10,374 g.

Category	Primary food	Secondary food	Primary product	Secondary product	Bags	Foils	Total
Bakery products	552	0	0	0	0	0	5,3%
Meat	570	0	0	0	0	0	5,5%
Household packaging	462	0	0	0	0	0	4,5%
Dairy	87	0	0	0	0	0	0,8%
Coffee	94	0	0	0	0	0	0,9%
Fresh produce	313	0	0	0	0	0	3,0%
Snack metallised	187	0	0	0	0	0	1,8%
Snack uncoated	106	0	0	0	0	0	1,0%
Frozen food / convenience	316	0	0	0	0	0	3,0%
Dry food	144	0	0	0	0	0	1,4%
Beverages / extra wrapping	0	591	0	0	0	0	5,7%
Construction / workshop	0	0	1362	0	0	0	13,1%
Garden	0	0	0	0	0	0	0,0%
Household products	0	0	518	0	0	0	5,0%
Sanitary products	0	0	396	0	0	0	3,8%
Toys	0	0	293	0	0	0	2,8%
Wet pet food	0	0	552	0	0	0	5,3%
Dry pet food	0	0	202	0	0	0	1,9%
Gift wrapping	0	0	0	64	0	0	0,6%
Mail order	0	0	0	1288	0	0	12,4%
Wrapping	0	0	0	4	0	0	0,0%
Carrier bags	0	0	0	0	435	0	4,2%
Bags	0	0	0	0	1525	0	14,7%
Foils	0	0	0	0	0	313	3,0%
Total	**2830**	**591**	**3323**	**1356**	**1961**	**313**	**10374**
Share	**27%**	**6%**	**32%**	**13%**	**19%**	**3%**	**100%**

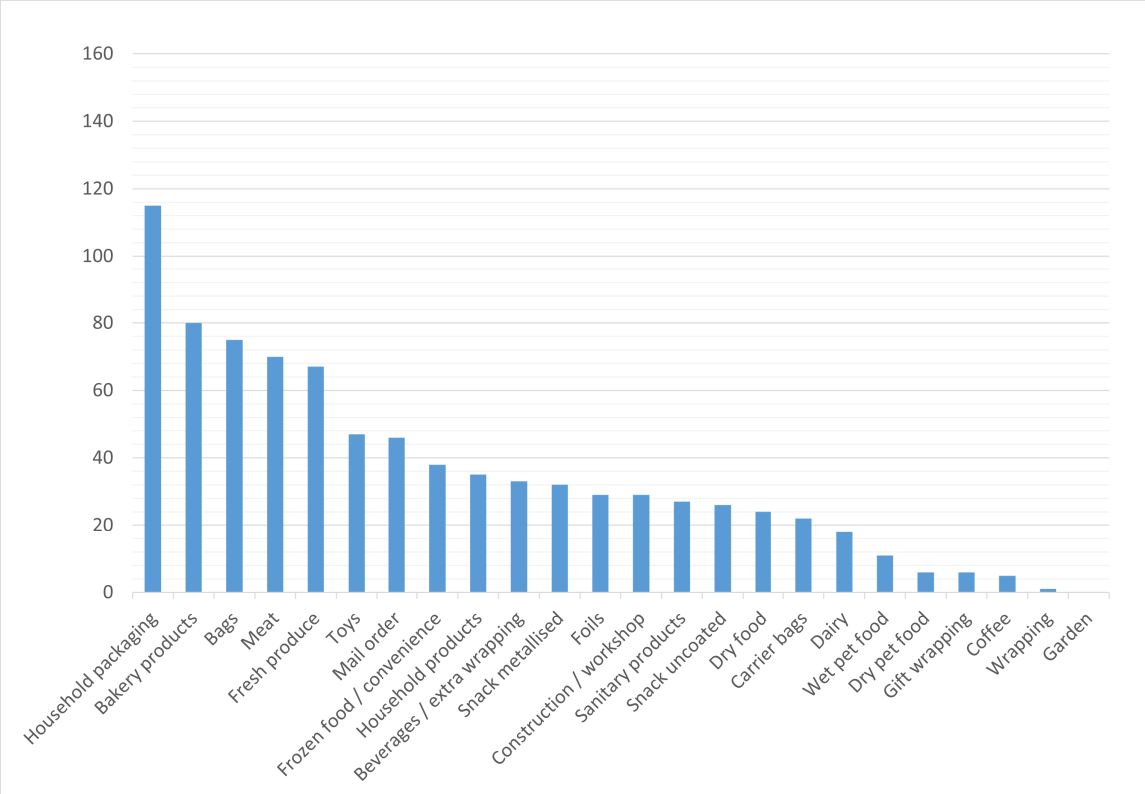


Figure 3.11.: Object distribution of the yellow bag sample according to category 2 ranked by the frequency of occurrence. Total n=842.

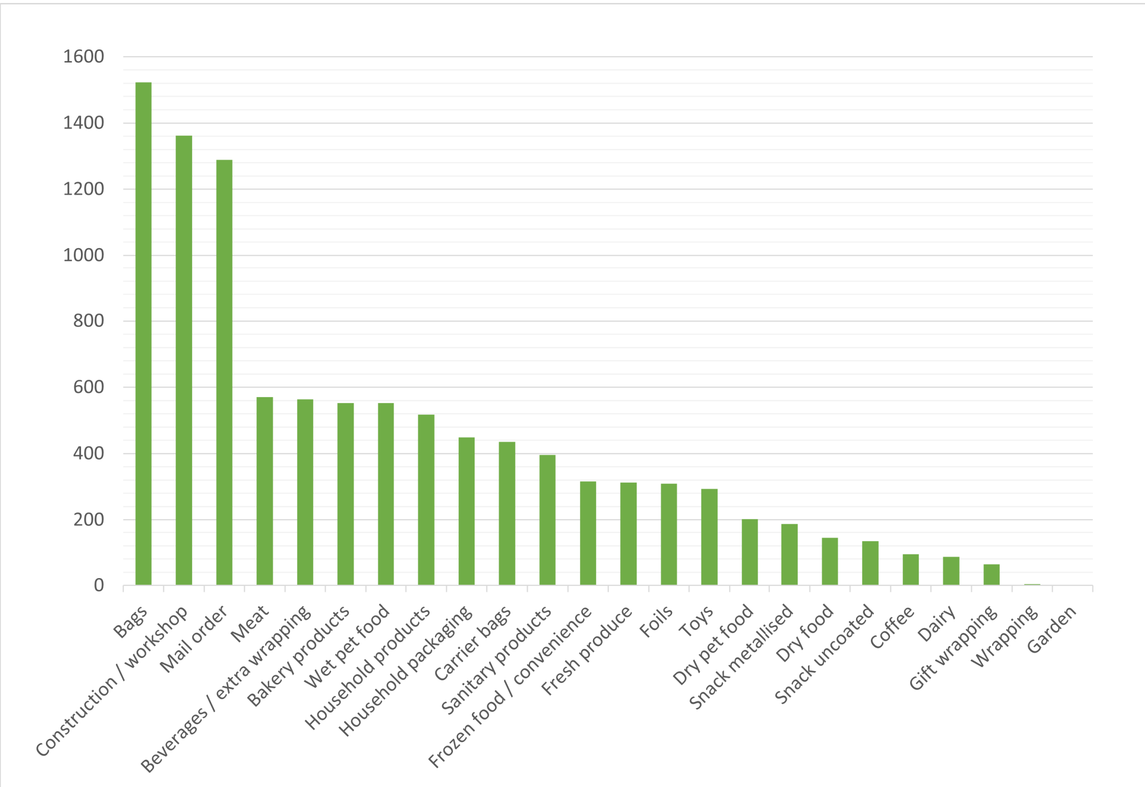


Figure 3.12.: Mass distribution of the yellow bag sample according to category 2 ranked by weight. Total m=10,374 g.

Quantification of Multilayer Films

Table 3.7 gives an overview of the findings of the FTIR-ATR analysis to quantify multilayer films in the two dimensional flexible foil fraction of the yellow bag. More information on the method used for the FTIR-ATR analysis and its limits are given in Section Material and methods. The total amount of identified multilayer films in the 2D fraction of the yellow bag sample results in 24 w-%. Multiplying the given share of multilayer films in the 2D yellow bag sample (24 w-%) with the overall share of 2D material on the yellow bag (26 w-%), the derived value for multilayer films in the yellow bag is 6 w-%. This hypothesis is strengthened by an article published by EU-Recycling Umwelttechnik 2018 which claims the share of multilayer films in flexible waste plastic packaging to be about 20 %. Thus, the magnitude of the percentage of multilayer films present in the yellow bag collection can be considered as reasonable. The three categories, primary food packaging (7.8 w-%), primary product packaging (7.9 w-%), and bags (7.2 w-%) contribute almost equally to the total value of 24 w-% of multilayer film in the 2D yellow bag material, compare to Table 3.6.

Table 3.6.: Assessment of multilayer film content according to category 1 in the yellow bag 2D sample.

Category 1	Unit	Primary food packaging	Secondary food packaging	Primary product packaging	Secondary product packaging	Bags	Foils	Total
Objects	[-]	72	3	23	9	17	20	144
Monolayer	[-]	39	2	16	8	15	19	99
Multilayer	[-]	33	1	7	1	2	1	45
Share multilayer	[%]	46%	33%	30%	11%	12%	5%	31%
Weight	[g]	453	32	1167	144	593	429	2818
Monolayer	[g]	229,8	28,4	944	573,6	226,9	126,6	2129,3
Multilayer	[g]	220,5	3,4	223,3	19,4	201,9	17,8	686,3
Share by category	**[w-%]**	**49%**	**11%**	**19%**	**13%**	**34%**	**4%**	**24%**
Share on total	**[w-%]**	**7,8%**	**0,1%**	**7,9%**	**0,7%**	**7,2%**	**0,6%**	**24%**

According to category 1, the most significant fractions, where multilayer films tend to accumulate, are primary food packaging and bags. Almost every second examined primary food packaging (share: 49 w-%) and every third generic plastic bag (share: 34 w-%) of the 2D yellow bag sample is made of multilayered film by weight. Whereby bags tend to be an outlier, since only two out of 17 inspected bag objects were identified as multilayer film, yet make up for 34 w-% of all analyzed multilayer films. One of the bags is especially heavy, creating the wrong impression of the bags category to accumulate multilayers. Also remarkable, hardly any multilayer films are to be found when it comes to secondary packaging in general. The same applies for generic foils.

Table 3.7.: Sample description and results of the FTIR-ATR analysis.

Nr	Sample ID	Description	Mass	Category 1	Category 2	IN	OUT	Multilayer
1	B1	Cereal Packaging inner layer	5,3	Primary food packaging	Dry food			
2	B2	Butter Madeleines	4,6	Primary food packaging	Bakery products			
3	B3	Toys	10,3	Primary product packaging	Toys	PP	PP	0
4	B4	Clothing bag	164,3	Primary product packaging	Household products	PE	PE	0
5	B5	Package of an apple turnover	4,6	Primary food packaging	Bakery products	PP	PP	0
6	B6	Manner Zarties Milky Vanilla	14,1	Primary food packaging	Snack uncoated	PE	PET	1
7	B7	Debreziner Spicy	7	Primary food packaging	Meat	PE	PE	0
8	B8	Cereal Bag inner layer	5,9	Primary food packaging	Dry food	PE	PP	1
9	B9	Ölz Mini Bussi Hazelnut	5,3	Primary food packaging	Bakery products	PP	PP	0
10	B10	Debreziner Spicy	6,9	Primary food packaging	Meat			
11	B11	Wachauer smoked pork belly	3,8	Primary food packaging	Meat			
12	B12	Berger ham foil	2,9	Primary food packaging	Meat	PE	PE	0
13	B13	Berger ham tray	11,6	Primary food packaging	Meat	PE	PA	1
14	B14	Mozzarella Light	3	Primary food packaging	Dairy	PE	PA	1
15	B15	Wachauer Knacker	5	Primary food packaging	Meat	PE	PA	1
16	B16	Ja natürlich breakfast bacon	2,9	Primary food packaging	Meat	PE	?	1
17	B17	Brioche plait	11,2	Primary food packaging	Bakery products	PP	?	1
18	B18	Scandinavian smoked salmon	2,9	Primary food packaging	Meat			
19	B19	Bell´arom Gold coffee	10,5	Primary food packaging	Coffee	PE	PP	1
20	B20	Omas Backstube Linzerstangerl	3,7	Primary food packaging	Bakery products	PP	PP	0
21	B21	Plastic bag	5,9	Bags	Carrier bags	PE	PE	0
22	B22	Organic fine oat flakes	6,8	Primary food packaging	Dry food	PE	PE	0
23	B23	Ferrara Spaghetti	3,1	Primary food packaging	Dry food	PP	PP	0
24	B24	Spar ready-to-bake pizza dough	6,4	Primary food packaging	Frozen food / convenience	PE	PET	1
25	B25a	Sbudget Pizza Dairy	6,2	Primary food packaging	Dairy	PE	PA	1
26	B25	Milbona Emmentaler	4,3	Primary food packaging	Dairy			
27	B26	Omas Backstube red currant bakery	3,1	Primary food packaging	Bakery products	PP	PP	0
28	B27	Tomato mix	2,6	Primary food packaging	Fresh produce	PP	PP	0
29	B28	Gutes vom Bäcker Doughnuts	5,9	Primary food packaging	Bakery products	PP	PP	0
30	B29	Transparent plastic bag	17,7	Bags	Carrier bags	PE	PE	0
31	B30	Hofer carrier bag	173,7	Bags	Carrier bags	PET	PP	1
32	B31	Salty sticks	9,1	Primary food packaging	Snack metallised	PE	PET	1
33	B32	Toppitz zipper bag	7	Primary food packaging	Household packaging	PE	PE	0
34	B33	Small plastic bag for snacks	6,6	Primary food packaging	Household packaging	PE	PE	0
35	B34	Veggini Nuggets	1,8	Primary food packaging	Frozen food / convenience	PP	PET	1
36	B35	Protective packaging	18	Secondary product packaging	Mail order	PP	PP	0
37	B36	Clothing bag	15,8	Primary product packaging	Household products	PP	PP	0
38	B37	Resch und Frisch Kornspitz	7,3	Primary food packaging	Bakery products	PP	PP	0
39	B38	Amazon mailing pouch	14,4	Secondary product packaging	Mail order	PE	PE	0
40	B39	Thurner Brioche plaite	5,2	Primary food packaging	Bakery products	PE	PA	1
41	B40	Salad hearts	3,9	Primary food packaging	Fresh produce	PP	PP	0
42	B41	Spar carrots	6,5	Primary food packaging	Fresh produce	PE	PE	0
43	B42	S Budget bread cubes	10,1	Primary food packaging	Bakery products	PP	PP	0
44	B43	Lego brick bag	1,7	Primary product packaging	Toys	PP	PP	0
45	B44	Bubble wrap	5,8	Secondary product packaging	Mail order	PE	PE	0
46	B45	Organic bag for fresh produce	1,8	Primary food packaging	Fresh produce	PE	PE	0
47	B46	Thin plastic tube	2,7	Secondary product packaging	Mail order	PP	PP	0
48	B47	Ölz butter toast	6,2	Primary food packaging	Bakery products	PP	PP	0
49	B48	Small plastic bag for snacks	1,5	Primary food packaging	Household packaging	PE	PE	0
50	B49	Bubble wrap	2,5	Secondary product packaging	Mail order	PE	PE	0
51	B50	HP Color Choice Toner	12,7	Primary product packaging	Household products	PP	PP	0
52	B51	Clever salty sticks	5,8	Primary food packaging	Snack uncoated	PP	?	1
53	B52	Der Gelbe Sack	60,9	Bags	Bags			
54	B53	Ikea zipper bag	4,2	Primary food packaging	Household packaging	?	PET	1
55	B53a	Milka chocolate	1,5	Primary food packaging	Snack uncoated			
56	B54	Sbudget ready-to-bake buns	11,3	Primary food packaging	Bakery products	PE/PP	PA/PP	1
57	B55	Transparent sheet	5,9	Primary product packaging	Household products	PP	PP	0
58	B56	Cling film	337,2	Secondary product packaging	Mail order	PE	PE	0
59	B57	Carrier film	17,8	Foils	Foils	PDMS	?	1
60	B58	Snipes shopping bag	30,2	Bags	Bags	PE	PE	0
61	B59	Plastic bag	45,8	Bags	Bags	PP	PP	0
62	B60	Piece of generic foil	2	Foils	Foils	PP	PP	0
63	B61	Transparent plastic bag	4,2	Bags	Bags	PE	PE	0
64	B62	Transparent plastic bag	5,4	Bags	Bags	PE	PE	0
65	B63	Transparent plastic bag	1,4	Foils	Foils	PE/PP	PE/PP	0
66	B64	NKD shopping bag	5,1	Bags	Carrier bags	PE	PE	0
67	B65	Post mailing pouch	4,7	Secondary product packaging	Mail order	PP	PP	0
68	B66	Klarsichtsack	4,3	Bags	Bags	PE	PE	0
69	B67	Weihnachtsfolie	3,1	Secondary product packaging	Gift wrapping	?	?	0
70	B68	Morawa mailing pouch	14,2	Secondary product packaging	Mail order	PE/PP	PE/PP	0
71	B69	FFP2 face mask packaging	2,6	Primary product packaging	Sanitary products			
72	B70	Landhof Cabanossi	7,1	Primary food packaging	Meat	PE	PET	1
73	B71	PP foil	1,2	Foils	Foils	PP	PP	0
74	B72	ekz foil	8,5	Foils	Foils	PE	PE	0
75	B73	Book wrapping film	2,1	Foils	Foils	PP	PP	0
76	B74	Plastic bag	5,7	Bags	Bags	PE	PE	0
77	B75	Cellophan gift wrapping	8,5	Foils	Foils	PP	PP	0

78	B76	Plastic bag	1,3	Bags	Bags	PE	PE	0
79	B77	Packaging of a ball-and-socket joint	44,9	Primary product packaging	Construction / workshop	PP	PP	0
80	B78	Foil	99,7	Foils	Foils	PE	PE	0
81	B79	Filter sand packaging	85,1	Primary product packaging	Construction / workshop	PE	PE	0
82	B80	Mailing pouch	114,1	Secondary product packaging	Mail order	PE	PE	0
83	B81	Foam inserts for mailing	9,9	Secondary product packaging	Mail order	PE	PE	0
84	B82	Lagerhaus wrapping film	514,5	Primary product packaging	Construction / workshop	PE	PE	0
85	B83	Blue plastic bag	22,4	Bags	Bags	PE	PE	0
86	B84	Dreamies	20,3	Primary product packaging	Wet pet food	PE	PET	1
87	B85	Cirkel Backstore shopping bag	34,1	Bags	Carrier bags	PE	PE	0
88	B86	Spar shopping bag	28,2	Bags	Carrier bags	PE	PET	1
89	B87	Gackerl Sackerl	4,5	Bags	Bags	PE	PE	0
90	B88	Coushion mailing wrap	15,4	Secondary product packaging	Mail order	PE	PE	0
91	B89	Eco plastic bag	3,6	Bags	Bags	PET/PA	PET/PA	0
92	B90	Nimm2 Lachgummi	3,6	Primary food packaging	Snack uncoated	PP	PP	0
93	B91	HDPE plastic bag	4,6	Bags	Bags	PP	PP	0
94	B92	Milka Noisette	2,2	Primary food packaging	Snack metallised	PE	PET	1
95	B93	Vegetable packaging	16,5	Primary food packaging	Fresh produce	PE	PET	1
96	B94	Chicken Wings BBQ	11,7	Primary food packaging	Frozen food / convenience	PE	PP	1
97	B95	Steakhouse pommes	11,8	Primary food packaging	Frozen food / convenience	PE	?	1
98	B96	Berger ham	5,5	Primary food packaging	Meat	PE	?	1
99	B97	Waldviertler potatoes	21,2	Primary food packaging	Fresh produce	PE	PE	0
100	B98	Fruity Snakes	3,5	Primary food packaging	Snack uncoated	PP	PE	1
101	B99	Metro product foil	3,1	Bags	Carrier bags	PP	PP	0
102	B100	Mailing pouch	1,8	Secondary product packaging	Mail order	PP	PP	0
103	B101	Snack peppers	2,1	Primary food packaging	Fresh produce	PP	PP	0
104	B102	Post mailing pouch	3,3	Secondary product packaging	Mail order	PP	PP	0
105	B103	Lagerhaus animal food packaging	129,7	Primary product packaging	Dry pet food	PE	PET	1
106	B104	Ginger Bisquits	0,9	Primary food packaging	Bakery products	PP	PP	0
107	B105	Farmers Country pistacchios	8,7	Primary food packaging	Dry food	PP	PP	0
108	B106	Solo hygienic sheets	7,1	Primary product packaging	Sanitary products	PE	PET	1
109	B107	Bauernland Erdäpfeltaler	12,3	Primary food packaging	Frozen food / convenience	PE	PE	0
110	B108	Wrapping of Disney bed linen	25,5	Primary product packaging	Household products	PP	PP	0
111	B109	W5 all-purpose cleaning sheets	5,9	Primary product packaging	Sanitary products	PE	PET	1
112	B110	Haribo Almdudler	3,1	Primary food packaging	Snack uncoated	PP	PP	0
113	B111	Crepes	3,2	Primary food packaging	Bakery products	PE	PP	1
114	B112	Thin plastic tube	1,8	Primary food packaging	Bakery products	PP	PP	0
115	B113	Packaging of a curtain	14,9	Primary product packaging	Household products	PP	PP	0
116	B114	Turbo briquettes	28,8	Primary product packaging	Construction / workshop	PE	PE	0
117	B115	Recheis egg pasta	35,2	Primary food packaging	Dry food	PE	PE	0
118	B116	Mens knee-highs	12,3	Primary product packaging	Household products	PE	PE	0
119	B117	Schärdinger Traungold	5,7	Primary food packaging	Dairy	PE	PET	1
120	B118	Sportgummi	4,2	Primary food packaging	Snack uncoated	PP	PP	0
121	B119	Coca Cola mini can wrapping	8,5	Secondary food packaging	Beverages / extra wrapping	PE	PE	0
122	B120	Neuburger cuts	4,5	Primary food packaging	Meat			
123	B121	Austrian peter root	3,4	Primary food packaging	Fresh produce	PE	PP	1
124	B122	Obi Shopping bag	20,6	Bags	Carrier bags	PE	PE	0
125	B123	Ja Natürlich bakery	8,3	Primary food packaging	Bakery products	PP	PP	0
126	B124	Kung Fu Panda pudding dessert	0,9	Primary food packaging	Snack metallised	PP	PP	0
127	B125	Nivex green beans	2,1	Primary food packaging	Fresh produce	PP	PP	0
128	B126	Rayher modelling clay	6,7	Primary product packaging	Toys	PE	PET	1
129	B129	Wawi wholemilk couverture	1,2	Primary food packaging	Dry food	PP	?	1
130	B128	Airplus bubble wrapping	26,5	Secondary product packaging	Mail order	PE	PE	0
131	B127	Toys	3,7	Primary product packaging	Toys	PP	PP	0
132	B128	Wettex	2,1	Primary product packaging	Household products	PP	PP	0
133	B129	Wieselburger beer can wrapping	15,5	Secondary food packaging	Beverages / extra wrapping	PE	PE	0
134	B130	Ölz mini cinnamon buns	1,2	Primary food packaging	Bakery products	PP	?	1
135	B131	Frosch detergent	46,6	Primary product packaging	Sanitary products	PE	PET	1
136	B132	Alpengut Gouda	3,4	Primary food packaging	Dairy	PE	PA	1
137	B133	Cookie bag	4,6	Primary food packaging	Bakery products	PP	PET	1
138	B134	Schär Meisterbäcker Vital	9,1	Primary food packaging	Bakery products	PE	PA	1
139	B135	Nanu Nana shopping bag	8,4	Bags	Carrier bags	PE	PE	0
140	B136	Tonibox	7	Primary product packaging	Toys	PE	PET	1
141	B137	Recheis ABC soup noodles	3,1	Primary food packaging	Dry food	PP	PP	0
142	B138	Spar mini muffins	8,4	Primary food packaging	Bakery products	PP	PP	0
143	B139	Dominosteine	1,5	Primary food packaging	Bakery products	PP	PP	0
144	B140	Spar napkin	1,5	Primary product packaging	Household products	PP	PP	0
145	B141	Fizzers Minis	3,4	Secondary food packaging	Beverages / extra wrapping	PP	PET	1
146	B142	Milka Naps	4,4	Secondary food packaging	Beverages / extra wrapping	PP	PP	0
147	B143	Berger Frankfurter	15,4	Primary food packaging	Meat	PE	PA	1
148	B144	Small plastic bag for snacks	0,8	Primary food packaging	Household packaging	PP	PE	1
149	B145	Ölz winter cake	4,8	Primary food packaging	Bakery products	PP	PP	0
150	B146	Cellophan gift wrapping	3,2	Foils	Foils	PP	PP	0
151	B147	Plastic tube	19,4	Secondary product packaging	Mail order	PE	PP	1
152	B148	Santa claus bag	5,6	Primary food packaging	Household packaging	PP	PP	0
153	B149	Fair Trade roses	6,1	Primary food packaging	Fresh produce	PP	PP	0
Total		n=143/153 objects identified	2818 g/2913 g identified					45

The distribution of samples according to category 2, given in Table 3.8, shows that concerning objects, multilayer films tend to accumulate in primary food packaging of the categories bakery products (16 %), meat (13 %), and dairy (9 %) followed by frozen food and convenience (9 %). Almost half the number of all multilayer film objects goes to their account. Yet, they only contribute about one third to the total weight of multilayer films. The most probable product categories, where multilayer films are to be found, are packaging of dairy products (100 %), coffee bags (100 %), sanitary products (100 %), pet food (100 %), deep-freeze and convenience food packaging (80 %), followed by meat (75 %) and packaging of snacks (50 %-67 %). The ranking is almost identical when comparing the product categories by their share of weight.
It has to be pointed out, that this ranking is partly flawed by the number of too few inspected specimen per group category e.g. only one piece of coffee packaging is inspected. Hence, values based on few samples must be considered with particular caution. Looking at the contribution of a specific category to the total amount of multilayer films, plastic shopping bags again distort the list by being heavier than any other specimen. They make up for 29 w-%. Second comes dry pet food with 19 w-%, third sanitary related products (9 w-%) followed ex aequo by packaging for meat and bakery products (7 w-%) and convenience food (5 w-%). In general, non-food packaging is most prevalent when it comes to shares of multilayer films by weight. Figure 3.14 depicts these observations in a more convenient manner.

Table 3.8.: Assessment of multilayer film content according to category 2 in the yellow bag 2D sample.

Category 2	Sample	Multilayer	Share of category	Share of total multilayer	Sample	Multilayer	Share of category	Share of total multilayer
	[pcs.]	[pcs.]	[%]	[%]	[g]	[g]	[w-%]	[w-%]
Bakery products	21	7	33%	16%	118	46	39%	7%
Meat	8	6	75%	13%	57	48	83%	7%
Household packaging	6	2	33%	4%	26	5	19%	1%
Dairy	4	4	100%	9%	18	18	100%	3%
Coffee	1	1	100%	2%	11	11	100%	2%
Fresh produce	10	2	20%	4%	66	20	30%	3%
Snack metallised	3	2	67%	4%	12	11	93%	2%
Snack uncoated	6	3	50%	7%	34	23	68%	3%
Frozen food / convenience	5	4	80%	9%	44	32	72%	5%
Dry food	7	2	29%	4%	64	7	11%	1%
Beverages / extra wrapping	4	1	25%	2%	32	3	11%	0%
Construction / workshop	4	0	0%	0%	673	0	0%	0%
Garden	0	0	0%	0%	0	0	0%	0%
Household products	9	0	0%	0%	255	0	0%	0%
Sanitary products	3	3	100%	7%	60	60	100%	9%
Toys	5	2	40%	4%	29	14	47%	2%
Wet pet food	1	1	100%	2%	20	20	100%	3%
Dry pet food	1	1	100%	2%	130	130	100%	19%
Gift wrapping	1	0	0%	0%	3	0	0%	0%
Mail order	15	1	7%	2%	590	19	3%	3%
Carrier bags	9	2	22%	4%	297	202	68%	29%
Bags	11	0	0%	0%	132	0	0%	0%
Foils	9	1	11%	2%	144	18	12%	3%
Total	143	45	31%	100%	2 816	686	24%	100%

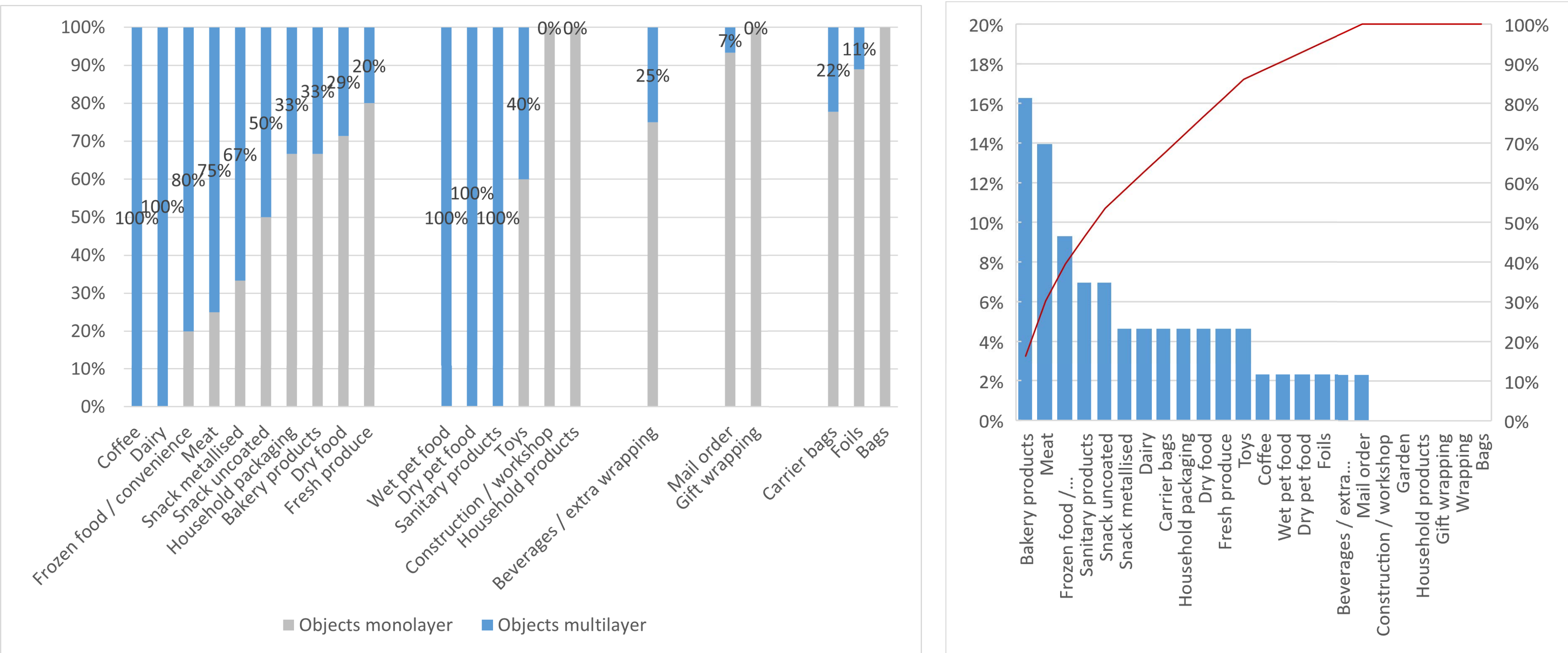


Figure 3.13.: Share of multilayer film objects by category 2 (left). Pareto diagram depicting the share of each category to the total objects of multilayer films (right).Sample n=143.

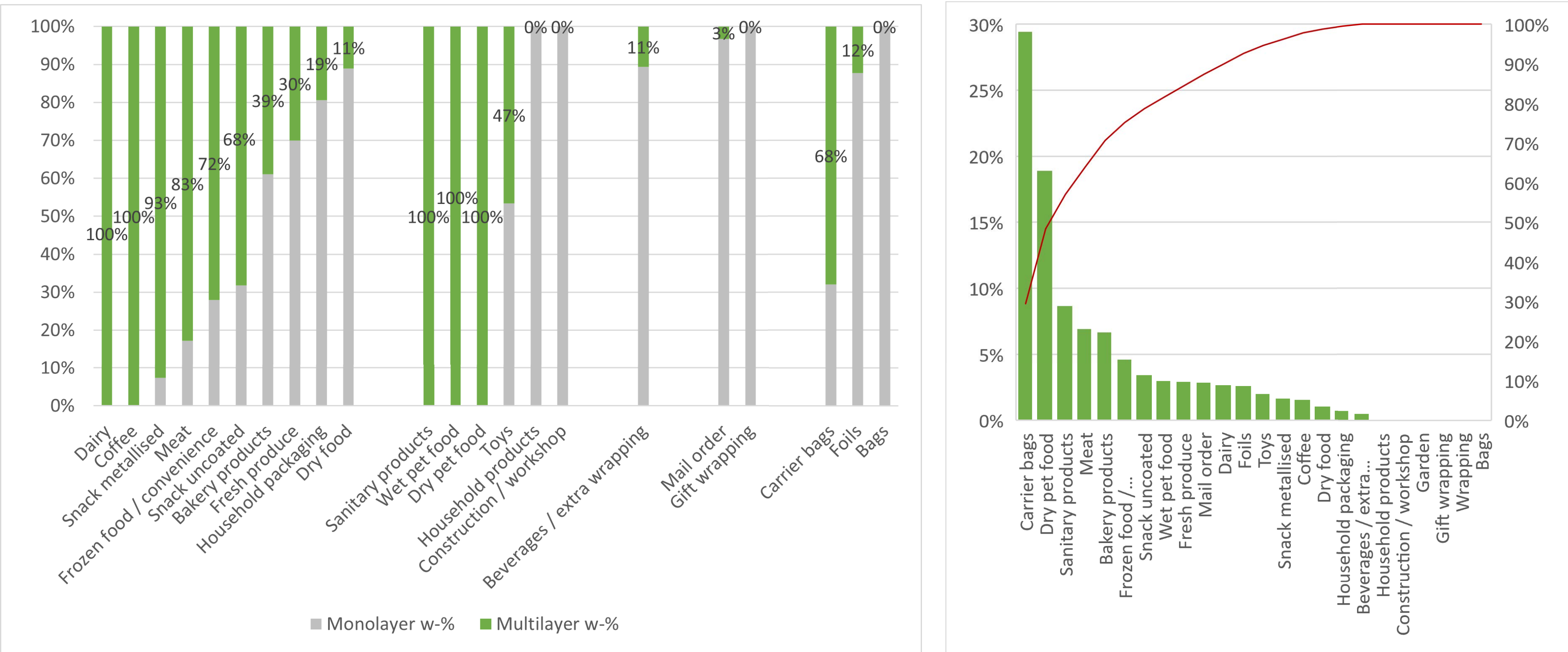


Figure 3.14.: Share of multilayer film by weight and category 2 (left). Pareto diagram depicting the share of each category to the total weight of multilayer films (right). Sample m=2,818 g

Identification of Multilayer Films

Figure 3.15 depicts on the left all superficial combinations of polymers of the 2D yellow bag sample identified by FTIR-ATR analysis. This investigation is done for every product category. The most common result is that the examined specimen is a monolayered material made of PE or PP. This is the case for 66 % of all 143 objects. The rest, in total 34 %, is considered to be multilayer film, since the material differs for the front and the back. Frequent combinations are made of PET, PE, PP or PA ranked by decreasing frequency. Some objects, like mail order, generic bags and foils are made of more exotic variations with mixtures of multiple resins like PE/PP, PA/PP, PET/PA and polydimethylsiloxane (PDMS). No item made of plain PET, PA nor PS and PVC was identified. For 10 samples no precise statement was possible for either the inner or the outer layer. Further calculations on composition and polymer material according to category 1 can be found in Table 3.9.

Table 3.9.: Material composition matrix of the sample according to category 1.

Category 1 - objects	PE	PP	PE/PP	PE/PA	PET/PE	PET/PP	PET/PA	PP/PA	other	?	Total
Primary food packaging	11	27	7	8	7	2	0	0	2	8	72
Secondary food packaging	2	1	0	0	0	0	0	0	0	0	3
Primary product packaging	5	11	0	0	7	0	0	0	0	0	23
Secondary product packaging	8	5	2	0	0	1	0	0	0	1	17
Bags	14	3	0	0	1	1	1	0	0	0	20
Foils	2	5	1	0	0	0	0	0	0	1	9
Total	42	52	10	8	15	4	1	0	2	10	144
Share	29%	36%	7%	6%	10%	3%	1%	0%	1%	7%	100%

Category 1 - weight	PE	PP	PE/PP	PE/PA	PET/PE	PET/PP	PET/PA	PP/PA	other	?	Total
Primary food packaging	109	121	39	59	61	6	0	0	14	44	453
Secondary food packaging	24	4	0	0	0	3	0	0	0	0	32
Primary product packaging	805	139	0	0	223	0	0	0	0	0	1167
Secondary product packaging	526	31	34	0	0	0	0	0	0	3	593
Bags	170	54	0	0	28	174	4	0	0	0	429
Foils	108	17	1	0	0	0	0	0	0	18	144
Total	1742	365	74	59	313	184	4	0	14	65	2818
Share	62%	13%	3%	2%	11%	7%	0%	0%	0%	2%	100%

Category 1 - weight	PE	PP	PE/PP	PE/PA	PET/PE	PET/PP	PET/PA	PP/PA	other	?	Share
Primary food packaging	6%	33%	53%	100%	20%	3%	0%	0%	100%	68%	16%
Secondary food packaging	1%	1%	0%	0%	0%	2%	0%	0%	0%	0%	1%
Primary product packaging	46%	38%	0%	0%	71%	0%	0%	0%	0%	0%	41%
Secondary product packaging	30%	8%	45%	0%	0%	0%	0%	0%	0%	5%	21%
Bags	10%	15%	0%	0%	9%	95%	100%	0%	0%	0%	15%
Foils	6%	5%	2%	0%	0%	0%	0%	0%	0%	28%	5%
Total	100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	100%

Category 1 - weight	PE	PP	PE/PP	PE/PA	PET/PE	PET/PP	PET/PA	PP/PA	other	?	Total
Primary food packaging	24%	27%	9%	13%	14%	1%	0%	0%	3%	10%	100%
Secondary food packaging	75%	14%	0%	0%	0%	11%	0%	0%	0%	0%	100%
Primary product packaging	69%	12%	0%	0%	19%	0%	0%	0%	0%	0%	100%
Secondary product packaging	89%	5%	6%	0%	0%	0%	0%	0%	0%	1%	100%
Bags	40%	12%	0%	0%	7%	41%	1%	0%	0%	0%	100%
Foils	75%	12%	1%	0%	0%	0%	0%	0%	0%	12%	100%

Regarding the previous findings, the product groups, where multilayer films tend to accumulate are bakery products, meat, and dairy, followed by frozen food and convenience. Exemplary, the material composition of the bakery related flexible plastic packaging is given in Figure 3.15 on the right. Most of the bakery packaging is made of plain PP. If the bakery packaging is multilayered, it mainly consists of a combination of PE-PA, PP-PE or PP-PET. Two specimen are a combination of PP and an unknown material. Meat packaging is either made of PE or a combination of PET, PA and PE. Flexible packaging of dairy related products are always a multilayer material consisting of PE-PET or PE-PA. Frozen food and convenience products are almost exclusively made of a combination of PE, PP and PET. Additional data for each product category can be looked up in the appendix.

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	42	8	15	8	0	0	0	0	3
PP	8	52	4	0	0	0	0	0	4
PET	15	4	0	0	0	0	0	0	1
PA	8	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	1
PE/PP	0	0	0	0	0	2	1	0	0
PA/PP	0	0	0	0	0	1	0	0	0
PET/PA	0	0	0	0	0	0	0	1	0
?	3	4	1	0	1	0	0	0	1

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	1	0	2	0	0	0	0	0
PP	1	14	1	0	0	0	0	0	2
PET	0	1	0	0	0	0	0	0	0
PA	2	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	1	0	0
PA/PP	0	0	0	0	0	1	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	2	0	0	0	0	0	0	0

Figure 3.15.: Matrix of all identified polymer combinations (left). Matrix of identified polymer combinations for the category bakery packaging (right).

Plausibility Check

The results of the DSC listed in Table 3.10 reveal that two specimen of the meat packaging category are indeed multilayer films instead of PE monolayer films. It is thus confirmed that a higher number of multilayer films in the sample is likely.

Table 3.10.: Results of DSC confirm false positive test of monolayers in the sample.

Nr.	Description	Category 1	FTIR-ATR IN	FTIR-ATR OUT	ML FTIR-ATR	ML DSC
B7	Debreziner Spicy	Meat	PE	PE	0	1
B12	Berger ham foil	Meat	PE	PE	0	1
B20	Omas Backstube Linzerstangerl	Bakery products	PP	PP	0	0
B28	Gutes vom Bäcker Doughnuts	Bakery products	PP	PP	0	0
B32	Toppitz zipper bag	Household packaging	PE	PE	0	0
B47	Ölz butter toast	Bakery products	PP	PP	0	0
B65	Post mailing pouch	Mail order	PP	PP	0	0
B95	Steakhouse pommes	Frozen food / convenience	PE	?	1	1
B101	Snack peppers	Fresh produce	PP	PP	0	0
B107	Bauernland Erdäpfeltaler	Frozen food / convenience	PE	PE	0	0

3.2.2. Assessment of Recycling potential and Estimated Contribution to the Austrian Plastic Packaging Recycling Efficiency

Recycling potential of multilayer films

In total, the hand sorting analysis revealed a multilayer film content of 6 w-% in separately collected waste (SCW). Multiplying the percentage of multilayer films in SCW by the total quantity of 171,000 tons of SCW in Austria, the recycling potential of multilayer films equals roughly to 10,260 tons, see Figure 3.16.

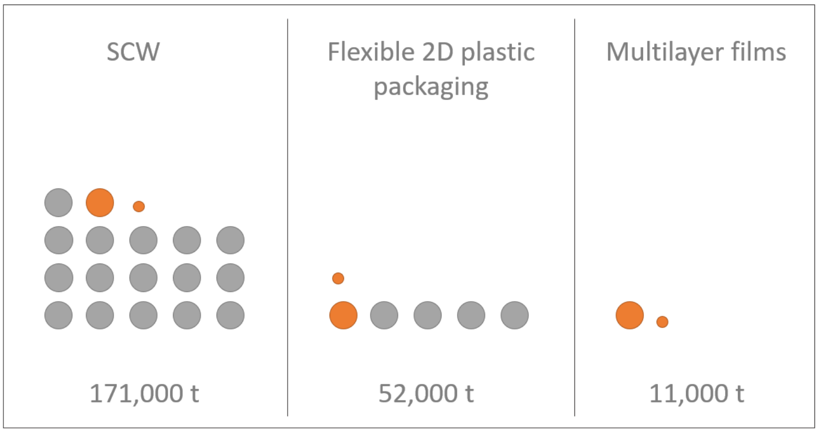


Figure 3.16.: Grafical illustration of the ideal recycling potential of multilayer films in comparison to the amount of the Austrian separately collected waste (SCW) and flexible waste plastic packaging.

Estimated Contribution to the Austrian Plastic Packaging Recycling Efficiency

Scenario 1 The detection and ejection of multilayer films is successful. But without any additional innovation, removing 10,260 tons multilayer films from SCW will result in a decrease of the recycling efficiency by 0.7 w-% from 25.7 w-% to a minimum of 25.0 w-%. In conclusion, more secondary resources are subject to industrial incineration and consequently lost to the material cycle. However, it has to be pointed out that this nonetheless has the incentive to improve the circularity of plastics by diversions profitability since the material properties of the remaining material, especially the mechanical properties, will improve, which, consequently, enables a broader palette of applications, decreases the need to add virgin material, and empowers the possibility of extra material loops. Instead of manufacturing low grade films and foils for waste bags and agriculture this could be one of the milestones to pave the way for higher quality products serving a broader market. Additionally, a material flow consisting of multilayer films enables future research on designated recycling processes.

Scenario 2 The detection, ejection and recycling of 10,260 tons multilayer films can ideally increase the Austrian recycling rate of plastic packaging waste by 3 w-% from 25.7 w-% to 28.7 w-%.

Scenario 3 The use of new advanced NIR sorting technology can additionally uncover previously untapped resource potential next to avoiding 10,260 tons of mulitlayer films in the product stream. It enables to separate the remaining flexible plastic packaging fraction even further into valuable clean monolayer streams and avoid co-incineration. Therefore, assuming that no more small plastic films have to be incinerated, an addition of 31,000 tons of small films can be recycled. So, in an ideal system with a successful detection and ejection rate of mulitlayer films of 100 % without incineration of small films, the theoretical recycling rate raises to a hypothetical maximum of 39.7 w-%. This highlights the significance of small films, its correlation to the recycling efficiency and the urge to act.

3.3. Considerations Regarding a Design Concept for an Experimental NIR Sensor Based Sorting Stand

The goal of this chapter is to answer research question 4.

1. "How could a design concept for a NIR spectroscopy sorting system look like, so that an identification of multilayer films is possible?"

3.3.1. NIR Spectroscopy

This section of the thesis is going to focus on the characteristics of near-infrared (NIR) spectroscopy, highlights why it got so popular, and will discuss its potential to identify multilayer films by the means of an adapted NIR sensor based sorting system. Since its rise in the early 90s, optical sorting technology made huge progress. Nowadays, NIR sensor based sorting is considered state-of-the-art in the field of waste management, when it comes to the recycling of waste plastics. It enables separation based on the chemical composition of a material equal to a fingerprint and allows the concentration of valuable goods before processing (Niaounakis 2020; Martens and Goldmann 2016). Mechanical separation and other sorting techniques are certainly also important for a holistic approach, but are beyond the scope of this thesis. For further information concerning this issue the reader is guided to specialised literature (Niaounakis 2020; Schubert 2003; Schloegl 2021).

3.3.2. Definition of NIR

NIR spectroscopy (NIRS) exploits interactions of a characteristic part of NIR radiation with the upper molecular layer of a material. By definition, the region of NIR denotes to the part of the electromagnetic spectrum in vicinity of the visible red light. It is a section of a larger region called infrared (IR), see Figure 3.17, that is subdivided into three sectors: the near-infrared (NIR, 700 nm - 2.5 µm), which is closest to the visible spectrum, the middle-infrared (MIR, 2.5 µm - 25 µm) and the far-infrared (FIR, 25 µm - 100 µm) (Ozaki et al. 2021). Typically, NIR radiation is specified in scientific literature by the wavelength (nm). For MIR and FIR the use of the wavenumber (1/cm) established itself (Pu et al. 2020).

3.3.3. Basic Principles of NIR Spectroscopy

This section provides fundamental information on the working principles and characteristics of NIRS and is going to discuss the advantages and limits of the interpretation of NIR spectra. According to Ozaki et al. 2021 and his book on NIRS, it is defined as follows:

> *"NIR spectroscopy is spectroscopy in the region of 12,000 - 4,000 1/cm, where bands arising from electronic transitions as well as those due to overtones and combinations of normal vibrational modes are expected to appear."*

NIRS is therefore directly connected to the electronic transition and to the change of the vibrational mode of a molecule. At ambient temperature, most molecules or atomic groups are at their fundamental vibrational state. The bonds between atoms of a molecule stretch and bend. In the ideal model, the movement corresponds to that of the harmonic oscillation of a mechanical spring. This is best explained by the classical mechanical model for a diatomic molecule, shown on the left hand side of Figure 3.18. In this model, two atoms are depicted by simplified masses (m1, m2). Their bond acts equal to a spring with a spring constant k. The freedom of movement is restricted to one single direction. According to the model, the motion complies to Hooke's Law. Hence, any displacement from the equilibrium position is restored without any loss. If one of the atoms starts to move, the motion leads to a displacement of the hypothetical

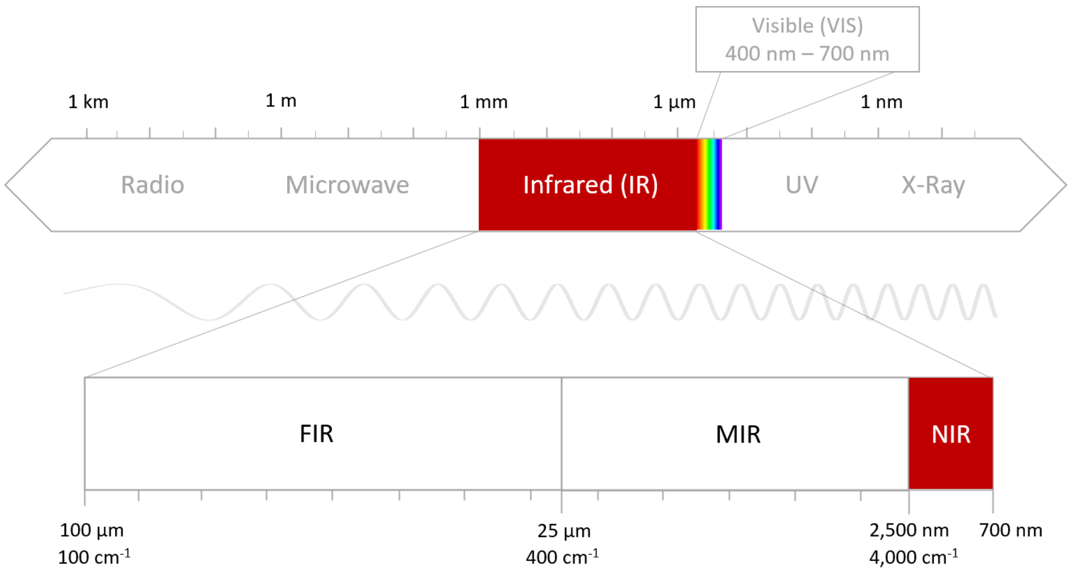


Figure 3.17.: Schematic view of the infrared region (IR), its sub-regions near-infrared (NIR), middle-infrared (MIR), far-infrared (FIR), and their location in the electromagnetic spectrum.

spring, which induces a periodic motion with the frequency ν, which is linked to k by the following relationship given by Equation 3.1, where µ stands for the reduced mass derived from m1 and m2.

$$\nu = \frac{1}{2\pi} * \sqrt{\frac{k}{\mu}} \tag{3.1}$$

This frequency of the spring reflects the normal mode of a molecule, ν_0, which refers to a couple of synonyms. It is also called normal frequency, normal vibration, ground vibration or the fundamental vibrational state of the molecule - which is often referred to as just the fundamental. But molecules often consist of more than two atoms and have a wider range of freedom of movement. They are able to stretch, rock, scissor, wag, and twist in or out of plane. Therefore, the following rule of $3N - 6$ can be applied to find the total number of fundamentals, whereby N stands for the number of nuclei. Linear molecules are an exemption from the rule, here the formula must be adapted to $3N - 5$. Exercising the formula for a non-linear water molecule with $N = 3$, the total number of fundamentals equals to three. All three vibrational modes (symmetric stretching (v1), bending (v2) and asymmetric stretching (v3)) are exaggeratedly depicted on the right-hand side of Figure 3.18.
A change in vibration is triggered by exciting a molecule by photon energy. This behavior is predicted by the Bohr frequency condition, given in Equation 3.2. It describes the transition of energy levels of a molecule from a certain level of vibration energy (E_m) to another (E_n) by absorbing the radiation energy $h * \nu$ of IR light.

$$h * \nu = E_n - E_m \tag{3.2}$$

With intensifying energy input, the interatomic distance (d) and potential energy (U) of a molecule increase. This connection is depicted in Figure 3.19 on the left-hand side for the model of the harmonic oscillator. The harmonic approach enables the understanding of the basic principles of NIR-spectroscopy. If the energy intake of the molecule reaches a certain threshold, a transition from the fundamental state ν_0 to its first excited state ν_1, the first overtone, occurs. If the energy intake doubles the molecule reaches the second excited state. Whereby the excited

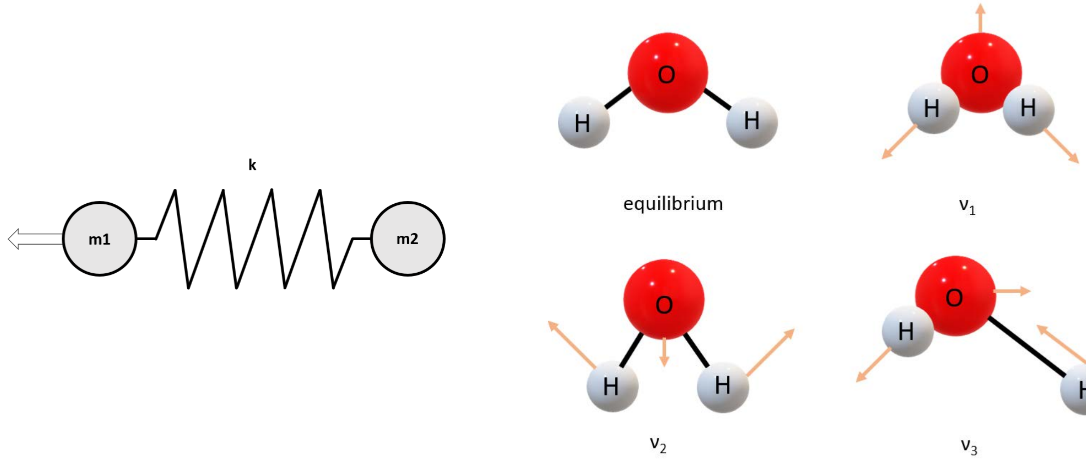


Figure 3.18.: Diatomic model of the harmonic oscillator (left) and the equilibrium geometry and the three normal modes of a water molecule (right). Picture is based on (Ozaki et al. 2021, p. 85)

state increases proportionally with the energy intake. However, this model does not depict reality. Repulsive and attracting forces caused by e.g. di-poles, influence the vibrating behavior on a quantum mechanic level and the model of the ideal spring does not apply. The harmonic model only allows transitions between adjacent energy levels of $\nu \pm 1$, although changes of $\nu \pm 2$ and $\nu \pm 3$ can definitely be observed. In fact, these transitions are typical for NIRS, since it mainly inspects the region of the electromagnetic spectrum where those multi-level transitions appear in the form of weak overtones and combinations of them. Therefore, Figure 3.19 on the right-hand side shows the model of the anharmonic oscillator. It resembles the model of the harmonic oscillator, but it has a skewed form, which considers the actual anharmonicity of molecule vibration. Another difference is the decrease of distance between energy levels with increasing energy. Additionally, it considers the possibility of a molecule to dissociate if a certain energy level above its dissociation energy is reached.

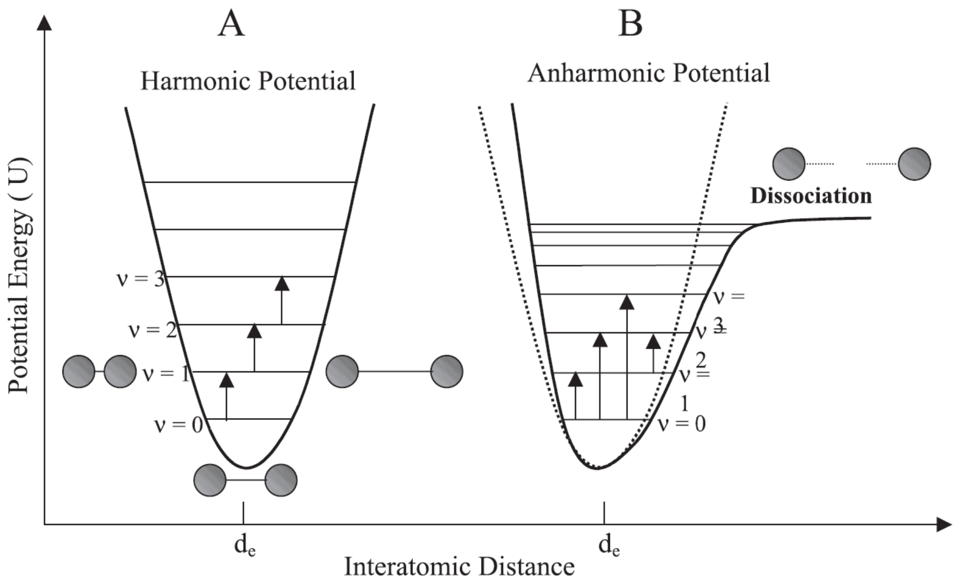


Figure 3.19.: The potential energy (U) of a molecule as a function of the interatomic distance (d) and its relation to the vibrational modes for the ideal model of the harmonic oscillator (left) and the real model of the anharmonic oscillator (right) (Pasquini 2003, p. 4)

Figure 3.20 shows the absorption spectra of three different chemicals: hexane, isoctane and toluene. It features typical NIR spectroscopic characteristics due to the absorbance of IR light resulting in the excitement of C-H bonds in the compounds. This is reflected by varying intensities of absorbance (y-axis) and shifts of the peak positions at certain wavelengths (x-axis) depending on chemical bonds in combination with hydrogen e.g. C-H, N-H, O-H, or S-H. The difference of these characteristic vibrational modes appearing in NIRS is exploited to enable qualitative analysis of samples. In addition, the effect of IR absorbance of molecules often obey Beer's law which means absorption is in linear correlation to the concentration of the examined sample. This allows for quantitative analysis via calibration e.g. starch content of rice, caffeine content of coffee, active ingredient content of medicines. Exemption to this rule are molecules with symmetric structure i.e. O_2, H_2, or N_2. When they are exposed to IR light, their dipoles are not stimulated to produce a characteristic anharmonicity. Hence, an IR spectrum does not exist. Such substances are also referred to as "IR inactive".

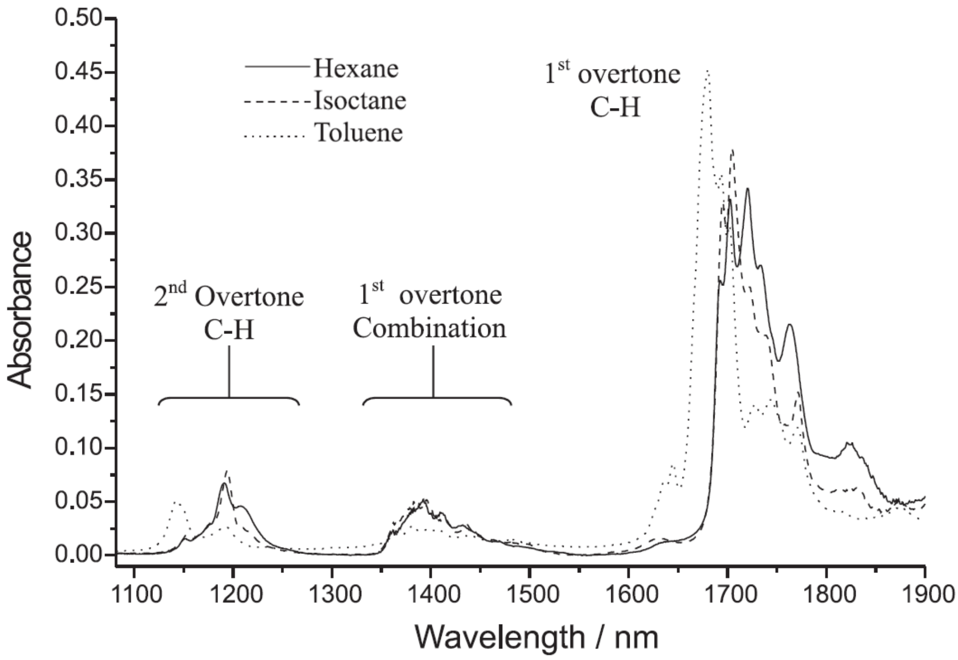


Figure 3.20.: Example NIR-spectra of different chemical compounds with visible overtone regions (Pasquini 2003, p. 12) acting as fingerprint.

3.3.4. Advantages and Limits of NIR Spectroscopy

Despite its complexity NIRS is useful in a wide range of industrial applications. It is considered as a robust and quick, non-destructrive, non-contact in-situ analysis that does not need any sample preparation. It is cheaper than comparable IR devices, yet comes with good signal to noise ratio and accuracy (Ozaki et al. 2021, p. 14). NIRS is agnostic to differing shapes, aggregate states and can tolerate a certain thickness of specimen. Inspected samples can be liquids, aqueous solutions or solids up to the diameter of an apple. The method produces a chemical fingerprint of the compound, which can be evaluated quantitatively or qualitatively. The only restriction to analysis is that it requires IR active material, which is not too glossy or reflecting and does not absorb IR radiation at a too high extent. On the downside, since NIRS only observes vibration overtones and combinations of them, which may overlap, the analysis of NIR spectra is not straight forward. The use of statistical methods, so called chemometrics, are necessary to prepare the spectral data for qualitative interpretation. However, companies nowadays offer ready to use software packages and reference data for well established NIR applications and relieve the non-scientific user of complicated evaluation tasks. Calibration enables quantitative analysis but the sensitivity is limited. If the sought substance is too diluted in a solution, its signal will be too strongly influenced by the surrounding matrix and thus hardly detectable or not detectable at all. Hence, matrix effects do increase with decreasing concentration of a substance in a given medium. The use of a reference sample is therefore recommended to cancel the effects of scattering. Polytetrafluorethylene (PTFE), ceramic plate, and gold are best used as reference materials for opaque samples (Ozaki et al. 2021, p. 232). If developing of an in-house method is unavoidable, it can quickly become costly. Such projects are often lengthy and strenuous, as they are often based on empirical iteration. Various set-up and environmental factors can affect the result and thus need to be researched thoroughly. These can be local concentration variations, optical variations, sample to sensor distance variations, sample speed variation, external (ambient) light, temperature variation of the sample or the environment, mechanical vibrations, power-line fluctuations, dust or (corrosive) vapors (Burns and Ciurczak 2008, p. 750). Nonetheless, NIRS is very versatile. The low energy impact of NIR enables a gentle non-invasive inspection of organic material. That is why it is so popular in medical applications. The devices for analysis range from mobile hand-held and stationary lab equipment up to rugged process analytical tools for automatic identification of samples. In the recycling industry, NIRS is used for optical sorting of input. It decouples the sorting criterion from the sorting force which enables a wide range of applications.

Table 3.11.: Compilation of advantages and disadvantages of NIRS (Ozaki et al. 2021; Niaounakis 2020; Burns and Ciurczak 2008; Pu et al. 2020)

+	-
In-situ analysis	Interpretation of results
Non-destructive analysis	Data pre-treatment
No sample preparation	IR inactive material
Non-contact analysis	High absorbing material
Suitable for thick samples	Light scattering
Liquid and solid samples	Transparency
Chemical fingerprint	Glossy, reflecting samples
Quantitative and qualitative	Empiric method development
Low energy application	Reference database necessary
Cheaper than comparable IR devices	Absorption bands overlap
Robust	High humidity or moist samples
Low maintenance cost	Rather low sensitivity limits
Good signal to noise ratio $10^5 : 1$	
Accuracy	

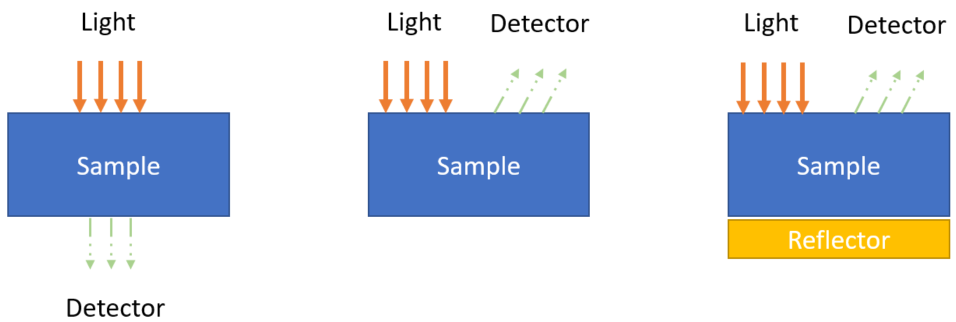
Instrumentation

Physically, a NIR spectrometer consists of four major parts: (1) light source, (2) spectrometer, (3) sample holder, (4) detector, and (5) analysis unit.

Light Source The light source is used to emit thermal radiation. It is recommended that it has its highest intensity at the wavelength range of interest, however this mostly applies to monochromatic light sources e.g. lasers (Günzler and Gremlich 2003, p. 40). In the wide application, the inexpensive and robust halogen lamps have prevailed. They are the most common method to achieve thermal radiation by resistive heating and provide white polychromatic light beyond the visible range with adequate intensity and has its emission peak at approximately 1 µm. Alternatives are heated nichrome wire and Glover (silicon carbide). If no wavelength array is desired, other technologies can be used as a source of light with a certain wavelength (monochromatic). One can choose between light-emitting-diodes (LED), laser diodes (LD) or solid-state lasers. They are often used in miniaturized NIR applications, e.g. LED in a pulse oximeter. An exemption is supercontinuum light, where laser pulses are led through a nonlinear optical material to emit a spectrum of light as output (Ozaki et al. 2021, pp. 212–214).

Spectrometer A spectrometer is an optical configuration to separate polychromatic light into discrete monochromatic frequencies or to prepare the latter before sampling (Günzler and Gremlich 2003). Different types of spectrometers exist on the market. They differ from each other by their way of selecting a certain wavelength or range of wavelength. The most simple spectrometer uses an optical bandpass filter. These optical filters are mounted on a (rotating) device, which allows only light of a certain wavelength to pass. The second type is a dispersive spectrometer. It uses either a prism or a grating system to split light into certain wavelengths. Whereby prisms are considered to be old fashioned and are continuously replaced by diffraction gratings (Ozaki et al. 2021, p. 215). Third is the Fourier-transform spectrometer (FT-spectrometer) which exploits light ray splitting by the means of a Michelson interferometer. An FT-spectrometer is very precise and accurate but is also large and expensive. This is why it is widely used as benchtop laboratory equipment. The fourth kind is an acousto-optic tunable filter (AOTF). At this method, external electrical modulation of an optical medium via ultra sonic waves allows to change the mediums refractive index. Therefore, the medium acts like a grating device and enables fast wavelength selection. This spectrometer is popular for industrial applications because of its design with non-movable parts, which makes it very robust (Pasquini 2003, p. 204).

Sample Holder A sample holder is a device made of an optical material that allows for the sample to be exposed to as much IR-light as possible without influencing the measuring process itself. NIRS is subdivided into three measurement modes according to the position of the detector in relativity to the sample. The three modes are transmittance, reflectance and transflectance mode, which is a combination of both, see Figure 3.21. The transmittance mode is commonly used for liquids. The NIR light is supposed to pass through the optical medium and the sample before detection. Therefore, NIR transparent materials are preferred in this configuration as sample holder e.g. cuvettes.



(a) Transmittance (b) Reflectance (c) Transflectance

Figure 3.21.: Different kind of NIR measurement methods according to Pu et al. 2020.

Often, materials that are transparent in the visible light are also transparent in the NIR region. Common materials are ordinary glass or fused silica (quartz). However, O-H impurities of the materials cause the appearance of their specific absorption bands in the measured spectra. This is why high grade purity materials are recommended for laboratory equipment, such as sapphire. But it comes with a high grade of reflection, decreasing the signal intensity. In addition, transmittance mode is susceptible to stray light. This is why it needs a controlled environment. In reflectance mode, any light reflected by the sample is detected. It is suited for bulky material of different shapes and sizes and is widely used in the recycling industry. However, it is very sample surface dominated and prone to specular reflection (Pasquini 2003, p. 208). Transflectance mode is a hybrid form of transmittance and reflectance mode. Like in transmittance light passes through the sample but in this modality, a high reflecting mirror material is installed as sample holder. The path of the light beam is thus doubled, as it has to enter the sample a second time after being reflected by the background. In this way, the beam intensity might decrease but its information increases, since the prolonged light path enhances interaction with the sample. One has to keep in mind that sample mounts or adjacent lab equipment might also reflect NIR light and disturb the measurement signal by light scattering. Such reflection can be prevented by using high absorbing black material or paint. Anodically oxidized aluminium also called black alumite is still reflecting 50% of NIR radiation (Ozaki et al. 2021, p. 224). Special attention has to be paid to cleanliness. Although dust is only slightly decreasing the signal intensity, it certainly promotes light scattering (Günzler and Gremlich 2003, pp. 40–41). Cui 2011 states that in the periodic system, transition metals are the most NIR reflective. This is why gold, silver, copper, aluminium and rhodium show the highest reflectivity in the NIR region. Gold exhibits excellent reflecting properties, yet it is not very affordable. Next to gold, aluminium is very popular because it is more cost-effective. But its reflectivity has a dip at a wavelength of 850 nm. Silver is a good compromise between the two metals. It reflects NIR radiation even with a thickness of 10 nm. A thin layer of vapor-evaporated silver is therefore commonly incorporated in sandwich-like multilayered mirrors. Figure 3.22 shows the relationship of reflectivity and wavelength for different metallic mirror materials in the NIR range.

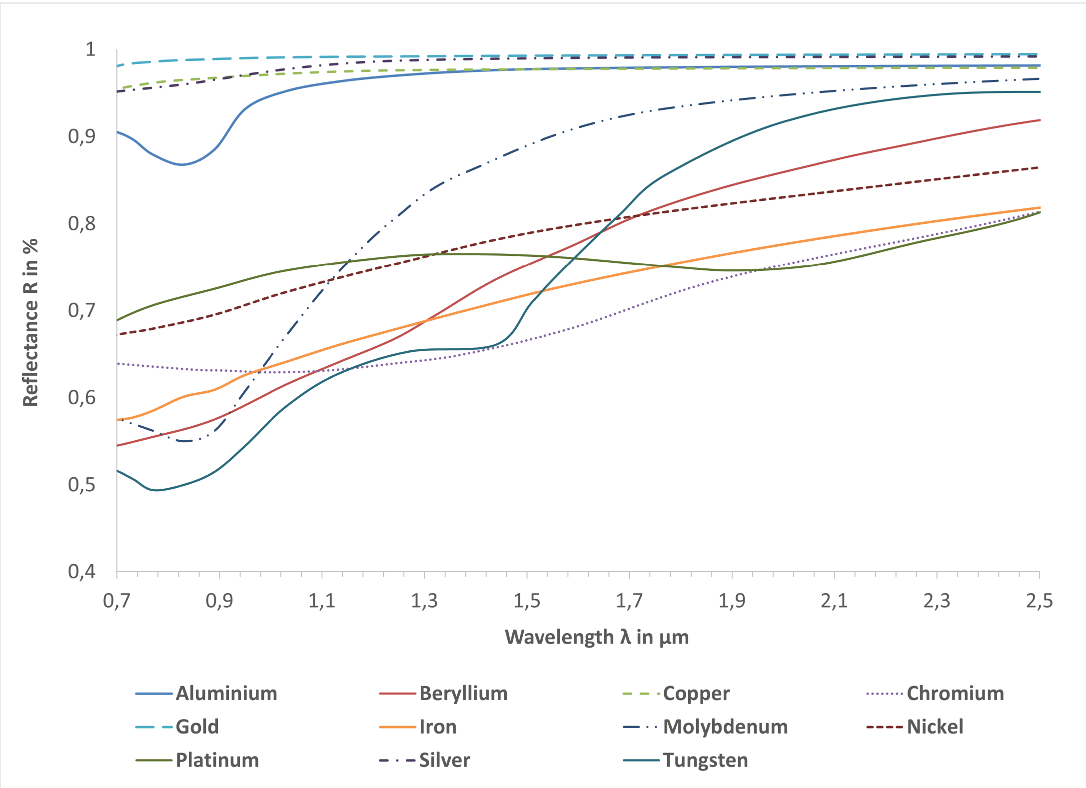


Figure 3.22.: Optical properties of different metals measured in normal incidence (Bass, Li, and van Stryland 2010, pp. 4.27–4.39).

Any optical material installed in an industrial NIRS device faces the challenge of combining high reflectivity concerning NIR radiation and durability since performance loss is often caused by environmental degradation processes (Hu et al. 2018).

Detector The detector of a NIR sensor system is responsible for capturing the emitted radiation of the sample. It collects the intensity of a defined light spectrum and converts it from an analog to a digital signal, exploiting different physical principles. Thermal detectors use either a change in thermoelectric voltage, electric conductivity or the pyro-electrical effect caused by radiation absorption. They are small and inexpensive, but tend to have a slow sampling rate. Photoelectric detectors are electronic semiconductors that directly interact with incoming radiation. The most cost-effective photoelectric detector is made of silicon (Si). For a better signal to noise ratio indium-gallium-arsenide (InGaAs) is considered as state-of-the-art. For further information, one can find extensive research on specific material for detectors in literature (Günzler and Gremlich 2003; Ozaki et al. 2021). Multiple of those detectors arranged in an array are called an NIR image sensor. It is able to cover a whole spectrum of different wavelengths simultaneously of a specific area. This design is the basis of hyperspectral imaging which is most commonly used in continuous monitoring of industrial processes.

Analysis Unit Signals of a NIR measurement can not be interpreted directly since the signal contains all chemical and physical information at once. The absorption bands overlap, or are ill defined overtones of such. Statistical methods are used to pre-treat data, to enhance the signal to noise ratio or to apply chemometrics. Consequently, a computing device is necessary to ingest and process all incoming analytical data. Product data sheets of different NIR sensor manufacturers provide information on the minimum requirements of the computing set-up depending on the type of NIR spectrometer and the degree of automation and complexity of the task.

Hyperspectral Imaging

The use of hyperspectral imaging in NIRS finds wide use in industrial applications since it can be employed as a continuous monitoring system. The use of chemometrics, a combination of mathematical and statistical analytics with chemistry, and a fast hyperspectral scanning rate paved the way of success of NIRS in food, pharmaceutical, polymer and recycling industry. The result of hyperspectral imaging is a three dimensional picture. Figure 3.23 illustrates an exemplary hyperspectral image. One can see the spatial (x,y) dimensions of the scanned area and the corresponding NIR spectrum at a certain wavelength (z). These three axes span a three-dimensional cuboid, with the depth containing the hyperspectral information of the inspected pixel in the x-y-plane. In qualitative analytics, the material will be examined and evaluated to determine whether there is a match with already known spectra.
According to Araujo-Andrade et al. 2021, four different modes of spectral image acquisition exist, see Figure 3.24. The point scan method analyzes the spectrum of one pixel at a time until the whole area of the sample is covered. The second is line scanning, or the pushbroom method. Here, a narrow line of the sample is spectrally analyzed by a two dimensional array of NIR detectors. It is the most common choice for automated inline integration. The third variant is the wavelength scan, or the staring method. The NIR signal of the sample is subject to a bandpass filter, which only allows a certain wavelength to pass before it is analyzed. Last but not least, is the snapshot method. This method analyzes a sample in one shot. The spectral information of a two dimensional array is collected simultaneously in multiple scans, which makes it perfect for static use.

NIR Spectroscopy Influencing Parameters

Optical and physical properties of flexible plastic waste pose a critical challenge to NIRS. Flexible packaging per-se is optically heterogeneous. It can be transparent, glossy or opaque. Their chemical composition is similar and so are their molar masses and densities. However, different

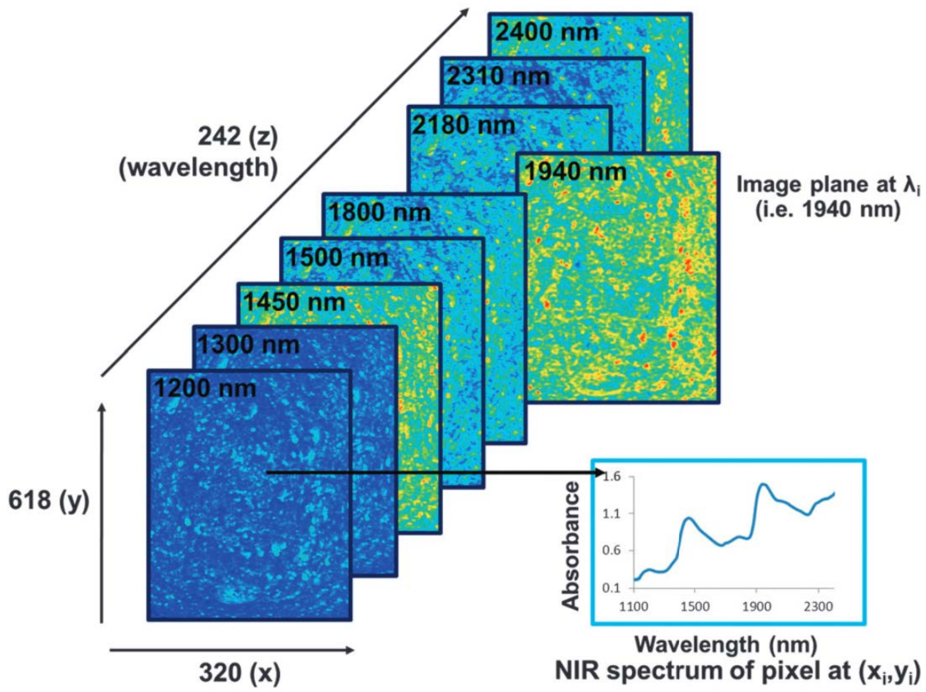


Figure 3.23.: Hyperspectral NIR image of a fresh bread loaf using false colours. The lush coloured parts mark the absorption bands of water deriving from the moisture in the bakery product. (Manley 2014, p. 8203).

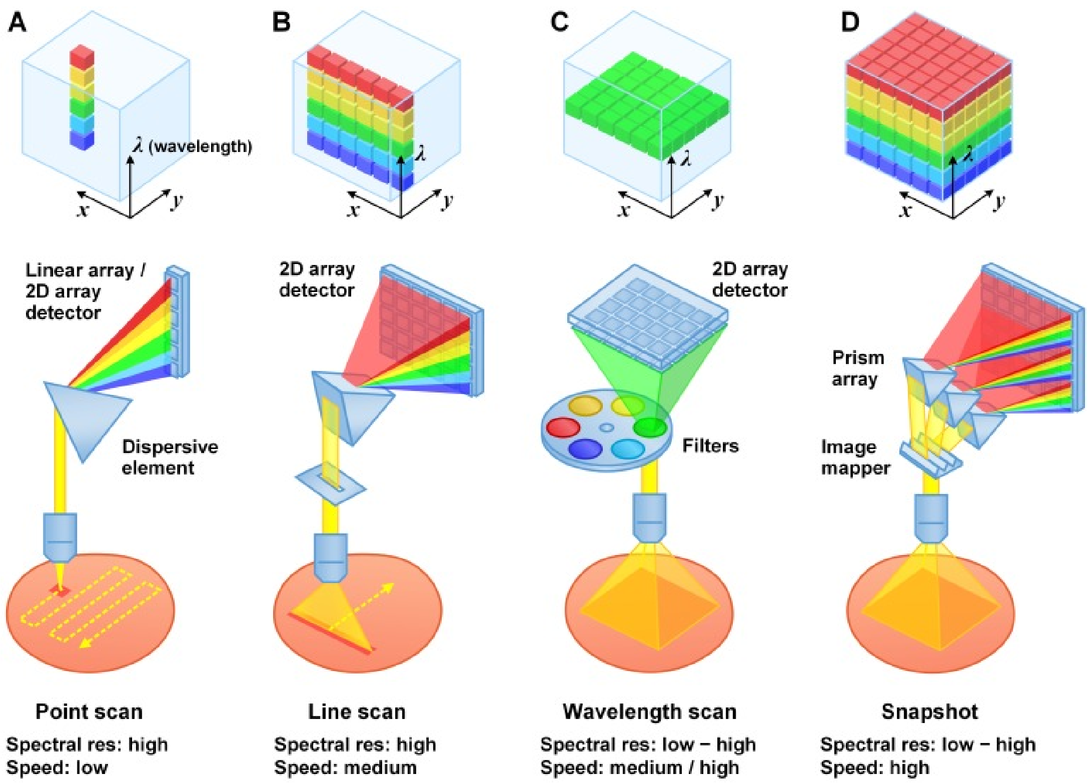


Figure 3.24.: Hyperspectral NIR image acquisition methods (Wang et al. 2017, p. 376).

additives and fillers critically change their physical properties. In addition, post consumer flexible packaging is subject to varying degrees of moisture, mechanical harm and debris of food, dirt or chemicals. All of which have a negative influence on the intensity or the NIR sampling signal itself e.g. an adherent contaminant appears as an absorption band in the NIR spectrum. In addition, flexible packaging is often made of very thin film. But a certain sample thickness is crucial for NIRS to promote absorption of the sampling signal by the near-surface molecules. Since there is less interference of the NIR beam with a thin sample, too thin films yield no useable NIR spectrum for classification. The sandwich-like structure of multilayered packaging film causes further loss of signal strength. On every transitions from one layer to another, the NIR signal is subject to reflection, absorption and transmission as a function of different refractive indices. The measurement signal of NIRS is in principle rather weak. More scattering due to multiple refraction weakens the signal even more (Ozaki et al. 2021, p. 224). In addition, thin sheets of foil restrict maximum belt speed and technical ejection opportunities. Other parameters affecting the results are signal noise and light scattering. Signal noise is caused by electronic equipment like the detector, amplifier or the AD-converter. Also, the experimental equipment itself can interfere with the measuring signal. Light scattering is either a result of specular reflection making the affected area unclassifiable or originates of NIR light being absorbed by the equipment surrounding the sample. Additionally, it can be produced by other light sources than the NIR emitter when alien light enters the detector. This can be because of insufficient shielding of the detector or reflections of mirroring surfaces e.g. chute material, which unintentionally alters the detected NIR signal. Other influencing factors are directly connected with the surrounding environment. This concerns temperature, disturbing gases (CO_2) present in the air, atmospheric humidity, cleanliness and changes of which (Günzler and Gremlich 2003, p. 158). Water vapor and moisture are known to influence NIR measurement since the absorbing bands of water appear in the spectrum. Next to the physical parameters are the ones on the computational side. Data pre-processing has great significance concerning the improvement of the signal to noise ratio. Typical are spatial correction for the optical set-up, bad pixel replacement, intensity calibration and noise suppression e.g. smoothing, or baseline correction. An extensive review of this subject is out of the scope of this thesis and the reader is guided to Rinnan, van Berg, and Engelsen 2009, Ozaki et al. 2021 or the Elsevier journal series "Trends in Analytical Chemistry" for further information. Last but not least, is the factor human and the spectral analysis method he chooses. The operator of the NIR sorting stand is responsible to pick adequate evaluation methods and characteristica of spectra to achieve reliable results with satisfactory precision and accuracy, be it for qualitative or quantitative analysis. The following enumeration summarizes the influencing parameters of NIRS. The first four parameters are directly linked with spectral quality, whereby the others are responsible for noise reduction and interpretability.

1. Sample properties
2. Signal noise
3. Light scattering
4. Ambient conditions
5. Data pre-processing
6. Evaluation methods

3.3.5. Enhancing Spectral Quality

The goal of this section is to formulate a design concept for the presented NIR sorting stand to enhance and research its ability to detect multilayer films in flexible waste plastic packaging. As discussed in the preceding paragraph, spectral quality is directly linked with sample properties. However, they must be considered as system inherent since there is no reasonable possibility to influence them. Therefore, based on the typical features of flexible waste plastic packaging, the derived NIR spectra are expected to be of poor spectral quality. A measure for spectral quality is the signal to noise ratio. Low values indicate that there is a high amount of meaningless signal, so called noise, in relation to the valuable information. Typical is an extensive deviation of the detected signal in the form of jittering without distinctive peaks of NIR absorption bands. Whereby high values imply that the signal inherits a substantial density of information ideally detected with low signal deviation, which manifests itself in distinct peaks. Therefore, to enhance spectral quality is to improve the signal to noise ratio. Parameters that are assumed to influence the signal side are the signal intensity and signal density. Noise can be reduced by eliminating unwanted spectral variations caused by e.g. varying ambient conditions, stray light or signal noise. In the following paragraphs, some promising ways in which this can be achieved will be outlined with regards to an experimental set-up of the presented NIR sorting stand.

Signal Intensity Even with low material thickness, increased irradiation could have a positive effect on the spectral quality, since more usable information could get back to the sensor despite the low reflection of thin-film materials. To amplify light intensity, the light emitting power of the halogen lamp should be set to the maximum. Any dust or dirt on the lamp should be removed to avoid any scattering of light. If possible, the halogen lamp can be exchanged for one with more power and better shielding against radiation loss. But with increasing light intensity spectral noise rises. However, it is considered to be beneficial to spectral quality since it is linked with a proportional rise of the signal to noise ratio (Ozaki et al. 2021, p. 240).

Signal Density A method to enhance signal density and signal intensity is the installation of a hemispheric diffuser to provide ideal Lambertian illumination of the samples (Ozaki et al. 2021, p. 481). Alternatives to the hemisphere are two opposing diffuser panels erected next to the conveyor belt or the chute. Both design concepts are depicted in Figure 3.25. They diffusely reflect the light of the emitter at their surface and also produce ideal illumination without any shadows or glare of the inspected samples. Optically, the geometry of the samples is reduced from a three dimensional to a two dimensional shape. Considering that only diffuse reflected light contains valuable hyperspectral information, this installation is very likely to have a positive effect on NIRS (Ozaki et al. 2021, p. 576).

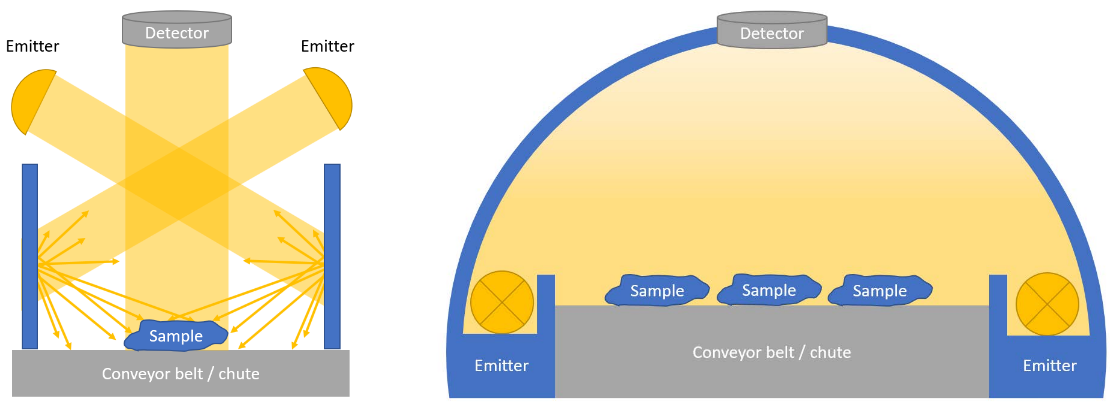


Figure 3.25.: Design concept for ideal Lambertian illumination of an in-line NIR sensor setup according to Ozaki et al. 2021, p. 576.

Another approach for better signal density is to change the measurement mode of NIRS from reflectance to transflectance. In transflection mode, NIR light passes the sample a second time after reflection by a mirroring background, see Figure 3.21. In this way, one can promote the possibility of the NIR signal to interact with the molecules of the sample by prolonging the path of the NIR radiation. Thus, the signals information content is expected to be increased. A variation of the chute material can have both a negative and a positive influence on the spectral quality and thus on the recording quality (Ozaki et al. 2021, p. 519). While materials that strongly absorb infrared rays degrade the spectral quality a highly reflective NIR inactive material has a positive influence on the spectral quality of the image. Aluminum turns out to be a very suitable material for that purpose, compare Figure 3.22 with a good price-performance ratio. It is recommended to test different grades in order to research the influence of the reflection dip around a wavelength of 800 nm. A mirror comprising a plated silver thin film in a protective sandwich structure is also very promising, yet more expensive. Silver also has the property of building up a sulphide layer, what effect this has on the reflectivity needs to be investigated.

Noise Reduction High noise levels lead to high spectral variation, which is unfavorable for developing robust qualitative and quantitative models. There are different kinds of noise. They can refer to changing ambient conditions, e.g. varying daylight, temperature or air humidity or noise coming from the electronic instrumentation itself. Their elimination is best practice, this is why they are already considered by the manufacturer of the given NIR set-up. One is able to select from a list of pre-defined methods in the supplied software to activate different types of noise suppression e.g. bad pixel replacement, spatial correction and signal noise suppression. No further insights in the applied methods are provided to the user apart from the ones stated in the user manual (EVK DI Kerschhaggl GmbH 2019, p. 25). It is nonetheless recommended to make use of them. Also, a black and white reference check should be done before every measurement series to cope with different degrees light intensities caused for example by change of daylight in an open set-up. On top of those fixed measures one can reduce unwanted spectral variations by shielding the set-up against stray light. This can be done by installing a hemisphere or any kind of housing made of NIR blocking material so that no alien light is able to enter the set-up. In addition it is recommendable to use absorbing photographers cloth or carbon black paint to cover parts of the experimental set-up to avoid light scattering by anything apart of the inspected sample (Ozaki et al. 2021, p. 224). Even when these measures do not raise signal intensity nor information density they ensure that the measuring signal is not disturbed. If there is still too much noise, there are other means to narrow it down and will be discussed in the next section.

3.3.6. Enhancing Spectral Evaluation

Besides spectral quality, one is able to improve spectral evaluation. This issue is not connected to the set-up itself, but depends on the operator. He decides to exploit distinct characteristics in the NIR spectra in order to establish a sorting model to identify multilayer films. Before any spectra can be evaluated, data pre-processing is necessary to alter the incoming sensor signal. The software provided with the experimental NIR sensor set-up (HELIOS SQALAR) allows to activate different modules to do so. Normalizing and smoothing increase the interpretability of the NIR signal. If the absorption bands of the signal are too weak for direct interpretation, the first or second derivative of the signal can be of help. This enhances the resolution and baseline correction of the signal. Next to data pre-processing, it is proposed to create a collection of spectra of different multilayer films. With a sufficiently large data base of reference materials one can exploit their spectral information for the selection of a representative sample set for calibration. At some point, distinct characteristics of NIR spectra are not visible anymore to the human eye. Multiple computing methods are at hand to conduct a more thorough analytical research to improve the calibration model even further. These methods may be roughly divided into three classes: (1) Exploratory Data Analysis, (2) regression analysis, and (3) classification techniques. The first technique includes data mining (e.g., Cluster Analysis, Principal Component Analysis (PCA)) which are used for gaining deeper insights into high-volume complex data e.g. a large set of NIR spectra. The second is used for the quantification of the content of a substance. The most utilized methods include Multiple Linear Regression (MLR), Principal

Component Regression (PCR) and Partial Least Squares Regression (PLSR). The third class sums up methods for the separation and sorting as well as grouping of samples with regard to a selected property. Classification approaches include supervised (e.g. Soft Independent Modeling of Class Analogy (SIMCA); Linear Discriminant Analysis (LDA); Partial Least Squares Discriminant Analysis (PLS-DA) or Support Vector Machine Classification (SVMC)) and unsupervised approaches (e.g., K-mean and K-median methods, Hierarchical Cluster Analysis or PCA, in its classification role). Without any detectable correlation, the use of artificial neural networks (ANN), locally weighed regression (LWR), and partial least squares 2 (PLS-2) can also prove to be effective, but demand for an even larger set of data. Every method has its own advantages and limits and needs to be thoroughly considered before applying it. For further information on this topic the reader is guided to Ozaki et al. 2021; Pu et al. 2020; Pasquini 2003; Burns and Ciurczak 2008; Reich 2005; Rinnan, van Berg, and Engelsen 2009. In this way it might be possible to exploit the fact that multilayer films consist of several layers with different refractive indices, which could affect the NIR spectra. If there is a demonstrable relationship, online detection of multilayer films is enabled. However, even if multilayer films could be detected as such in that way, it might not be possible to distinguish different types. Another point to investigate is to correlate parts of the NIR signal to a typical component of a multilayer film e.g. EVOH or maleic anhydride modified PE, which are common barrier and tie layer material of more complex multilayer films. With the realisation of an actual correlation, the sorting of multilayer films can be realised on the basis of these spectral differences.

4. Conclusion

This section summarizes the answers to research question of the thesis. In addition, it will give an outlook for future development which will be useful to provide direction for future studies.

4.1. Research Question 1

1. What are the challenges of flexible plastic waste recycling and why are multilayer films not being recycled and what does it take?

To summarize, based on the present analysis of an example plastic packaging recycling plant in combination with expert interviews, the following challenges for improving the recycling process of flexible plastic packaging, listed in a non-ranking order, could be identified: (1) Feedstock, (2) plant set-up and process technology, (3) personnel, (4) quality assessment, (5) by-products, and (6) the secondary raw material market. Multilayer films are not being recycled, because the current methods to do so are very restricted. Next to state-of-the-art sorting techniques for flexible packaging in general, mechanical recycling technologies are scarce (Niaounakis 2020; Schloegl 2021). Since multilayer film composites are a uniform structure of multiple very thin sheets ranging from 30 µm to 200 µm glued together the task to physically detach the single layers from each other is mechanically unfeasible due to the permanent nature of their joining technology. Therefore, attempts are currently under research to chemically recycle multilayer films, for example by OMV 2021 and BASF 2019. Nonetheless, they need clean feedstock to do so, but it lacks of technology to detect and sort multilayer films on-line on a plant scale from the vast volume of flexible packaging. Ecodesign or design for recycling can be a viable tool to increase the recycling of multilayer films. A more environmentally friendly design with removable or self detaching parts when shredded consisting of monomaterial, or fewer different types of materials, can have a consistently positive impact on the subsequent recycling chain.

4.2. Research Question 2

2. "Which share of the yellow bag is contributed by multilayer films and in which product groups do what kind of multilayer films accumulate?"

The total share of multilayer films in the yellow bag is 6 w-%, whereby the fraction is 24 w-%. The 24 w-% are almost equally split by the categories primary food packaging (7,8 w-%), primary product packaging (7,9 w-%), and plastic bags (7,2 w-%). The main packaging groups in which multilayer films tend to accumulate are primarily food packaging (share 49 w-%) followed by generic plastic bags (34 w-%), and primary product packaging (19 w-%). Bags tend to be an outlier, two out of 17 inspected bag objects were identified as multilayer film but make up for 34 w-% of all found multilayer films. One of the bags is especially heavy, giving the wrong impression of the bags category to concentrate multilayers. Also remarkable, hardly any multilayer films are to be found when it comes to secondary packaging in general. The same goes for generic foils.
Concerning primary food packaging, multilayer films tend to especially accumulate in packaging of bakery products (16%), meat (13%), and dairy (9%), followed by frozen food and convenience (9%). Almost half the number of all multilayer film objects goes to their account. Yet, they only contribute about one third to the total weight of multilayer films. The most probable product categories, where multilayer films are to be found, are packaging of dairy products (100%), coffee bags (100%), sanitary products (100%), pet food (100%), deep-freeze and convenience food packaging (80%), followed by meat (75%) and packaging of snacks (50%-67%). The ranking is almost identical when comparing the product categories by their share of weight.

It has to be pointed out, that this ranking is partly flawed by the number of too few inspected specimen in general and per group category e.g. only one piece of coffee packaging has been inspected. Hence, values based on few samples must be considered with particular caution. In general, non-food packaging is most prevalent when it comes to shares of multilayer films by weight. First are plastic shopping bags distorting again the list by being heavier than any other specimen, when looking at the share of weight that multilayer films contribute to that specific category. They make up for 29 w-%. Second comes dry pet food with 19 w-%, third sanitary related products (9 w-%) followed ex aequo by packaging for meat and bakery products (7 w-%) and convenience food (5 w-%). To summarize, multilayer films tend to be numerous, light weight and typically accumulate in primary food packaging. Few, but heavy specimen of multilayer films are to be found in product packaging.
The result of the FTIR-ATR analysis shows, that multilayered material is commonly made of a combination of PE-PET, PE-PP, PE-PA or PP-PET ranked by decreasing frequency. Some objects are made of more exotic mixtures of multiple resins like PE/PP, PA/PP, and PET/PA. Regarding the previous findings, the product groups, where multilayer films tend to accumulate are bakery products, meat, and dairy, followed by frozen food and convenience. Most of the bakery packaging is made of plain PP. If the bakery packaging is multilayered, it mainly consists of a combination of PE-PA, PP-PE or PP-PET. Meat packaging is either made of PE or a combination of PET, PA and the former. Flexible packaging of dairy related products are always a multilayer material consisting of PE-PET or PE-PA. Frozen food and convenience products are almost exclusively made of a combination of PE, PP and PET.
Please note the limited reliability of the hand sorting analysis and that it is not representative for a larger population.

4.3. Research Question 3

3. "How could the recycling of multilayer films contribute to a circular economy?"

Based on the hand sorting analysis, the examination of specimen with FTIR-ATR and the fundamental figures provided by the MFA of Van Eygen, Laner, and Fellner 2018, the ideal recycling potential of multilayer films in the Austrian separately waste collection is 10,260 tons per year, within the given limits of plausibility. Currently, the Austrian plastic packaging recycling efficiency is 25.7 w-%, since 77,000 tons of 300,000 tons of waste plastic packaging are mechanically recycled.
The examination of three different scenarios (1) Business as usual, (2) New technologies, and (3) Zero Waste examine the hypothetical contribution of recycling of multilayer films and the developments accelerated by the project Multilayer Detection to the Austrain plastic packaging recycling efficiency.
In scenario 1 innovation accelerated by project Multilayer Detection enables detection and targeted ejection of multilayer films. The rest of the plastic is recycled according to business as usual, which means the lion share is industrially incinerated and hardly any multilayer films are recycled because of a lack of technology. Until the development of new techniques to an industrial scale, multilayered films are considered to remain subject to industrial incineration after being ejected from the mechanical recycling stream. Thus, without taking any further action, removing multilayer films from SCW will result in a decrease of the recycling efficiency by 0.7 w-% to a minimum of 25.0 w-%. However, it has to be pointed out, that this nonetheless improves the circularity of plastics by diversions profitability since the material properties of the remaining material, especially the mechanical properties, will improve. This is going to enable a broader palette of applications, decrease the need to add virgin material, and empowers the possibility of extra material loops. Instead of manufacturing low grade films and foils for waste bags and agriculture this will be one of the milestones to pave the way for higher quality products serving a broader market. Additionally, a concentrated material flow consisting of multilayer films

enables future research on designated recycling processes.
In scenario 2 the detection and ejection of multilayer films is complemented by a designated recycling process. Therefore, in an ideal system with a successful detection and ejection rate of mulitlayer films of 100 %, recycling of multilayer films can ideally increase the Austrian recycling efficiency by 3 w-% to an ideal of 28.7 w-%, with the same benefits for product quality caused by their removal as stated in scenario 1.
Scenario 3 reflects a zero waste future. New technologies to detect, eject and recycle multilayer films are available and in use on an industrial scale. In addition, those innovations tap the previously uncovered recycling potential of small films by enhancing sorting depth of legacy sorting systems e.g. NIR sorting. Ideally, co-incineration of small films and multilayer films is fully replaced by 100 % mechanical recycling. Next to avoiding 10,260 tons of mulitlayer films in the product stream an addition of 31,000 tons of small films can be recycled, what results in a theoretical rise of the plastic recycling efficiency from 25.7 w-% by 14 w-% to a hypothetical maximum of 39.7 w-%. As a result, this allows to avoid a significant amount of waste generated along the recycling process and a new, value-added source of secondary resources is created. Productivity rate and the recycling efficiency of a recycling plant will increase which contributes to a sustainable recycling of plastics which additionally enhances product quality. This highlights the significance of small films next to multilayer films, its correlation to the recycling efficiency and the urge to act.

4.4. Research Question 4

4. "How could a design concept for a NIR spectroscopy sorting system look like, so that an identification of multilayer films is possible?"

Material properties of multilayer films make their identification by the means of NIR spectroscopy quite challenging. Based on their sample properties, poor spectral quality is to be expected but it is crucial when it comes to detecting and differing very similar NIR spectra. However, sample properties can not be manipulated since they are inherent in the system. Anyhow, there are ways to alter the design of the in-house experimental NIR sensor based sorting stand to enhance spectral quality which consequently improves the NIR signal. But the ways to intervene in the system are limited, since the NIR sensor system itself is encapsulated. A significant part of the data preparation is also not accessible. One is able to select from a list of pre-defined methods in the supplied software to activate different types of noise suppression e.g. bad pixel replacement, spatial correction and signal noise suppression. One has to trust that the manufacturer has made considerations according to best practice. Also, no calibrations can be performed on-site apart from a black and white reference adjustment. What remains to be influenced by the user are parameters regarding spectral quality and spectral evaluation. Spectral quality is a function of signal intensity and signal density. The easiest change of the former is to set the power of the emitter to maximum. In addition, the installation of a diffuser hemisphere or panels next to the conveyor belt is recommended. They provide ideal Lambertian illumination and promote diffuse reflection of the samples. Consequently, the signal density is expected to rise since more diffusive reflected light reaches the NIR detector.
Another opportunity to enhance spectra is to switch NIR measurement from reflection to transflection mode. In transflection mode, NIR light passes the sample a second time after reflection by a mirroring background. In this way, one can promote the possibility of the NIR signal to interfere with the molecules of the sample. Thus, the signal density is expected to be amplified. Another opportunity is to change the chute material to provide an ideal reflection surface for transflection mode. One has to keep in mind, that the variation of the chute material can have both a negative and a positive influence on the spectral quality. While materials that strongly absorb infrared rays degrade the spectral quality, a highly reflective, NIR inactive material has a positive influence on the spectral quality of the NIR image. It is therefore recommended

to test different grades of aluminium, since it has good reflective qualities with a good price-performance ratio. A mirror comprising a plated silver thin film in a protective sandwich structure is also very promising, yet more expensive. Finally, it is proposed to adapt the experimental NIR sensor based sorting system step by step according to the presented measures and to conduct a series of tests that will provide answers to the following research questions.

1. What influence does the illumination intensity have on the spectral quality?
2. Can the spectral quality be changed by the use of a diffuser?
3. What influence does the change of the measurement mode have on the spectral quality?
4. Can the spectral quality be changed by the chute material?

After the assessment of all parameters the best settings and modifications are to be retained to collect NIR spectra of multilayer films in enhanced spectral quality. These spectra are then used to establish a library of high quality multilayer film spectra, which is ready to use for calibration or advanced spectral evaluation.

4.5. Outlook

It is recommended to inspect the presented exemplary flexible waste plastic packaging recycling plant further to validate given and calculated information. For example, a material flow analysis on a substance level can provide the necessary insights on the inner processes to clarify the recycling routes of different resins that enter the recycling plant.
In the future, the research of recycling technologies of multilayer film and improvement of legacy plastic sorting technologies can help to further refine the sorting performance and tap unlocked recycling potential in the fraction of flexible plastic packaging waste to thus pave the way for a circular plastics economy away from mere use in industrial incineration. With regards to the recycling set-up of flexible waste plastic packaging, changes of the process and the plant set-up are considered to be the most promising field of future research and development. Investigation of the washing section and its efficiency to remove fines, inks and odour, improvement of the melt filtration technology, research of the use of compatibilizers in the recycled material, inclusion of color sorting to control product pigmentation and an upgrade of the legacy NIR sorting system are acknowledged with a good perspective to have a significant impact on product quality and quantity. NIR sensor based sorting is already state-of-the-art in many industrial areas, yet its research potential is far from exhausted and project Multilayer Detection takes the first step in this direction. Issues for further research and development of NIR spectroscopy are the build up of a multilayer films spectra library, their actual identification, and separation of different types of mono layer plastics e.g. according their manufacturing method or even by their amount of selected additives. It is recommended to adapt the presented experimental NIR sensor based sorting system according the proposed measures and exercise sorting test to disprove or validate improvement on spectral quality.

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List of Abbreviations

ACR	acid co-polymer resin
Al	Aluminium
AlOx	Aluminium oxide
APC	Air pollution control
ARA	Altstoff Recycling Austria AG
AS	automatic sorting
BOPET	Biaxially oriented polyethylene terephthalate
BOPP	Biaxially oriented polypropylene
DSC	Differential scanning calorimetry
EAA	Ethyleneacrylic acid
EMA	Ethylenemethacrylate
EMAA	Ethylenemethacrylic acid
ERP	Enterprise resource planning
EVA	Ethylene vinyl acetate
EVOH	Ethylene vinyl alcohol
FTIR	Fourier-transform infrared spectroscopy
FTIR-ATR	Fourier-transform infrared spectroscopy with attenuated total reflectance
HDPE	High density polyethylene
ID	Identification
ION	Ionomer
KPI	Key performance indicator
L1	Line 1
L3	Line 3
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
MFA	Material flow analysis
MFR	Melt flow rate
MGS	Maximum grain size
ML	Multilayer films
mLLDPE	metallozene linear low density polyethylene
MS	manual sorting
NAV	Nonsense placeholder variable of an ERP System for a good
NIR	Near-infrared
NIRS	Near-infrared spectroscopy
Nr	Number
OPA	Oriented polyamide
OPP	Oriented polypropylene
OPET	Oriented polyethylene terephthalate
PA	Polyamide
PCCL	Polymer Competence Center Leoben
PDMS	Polydimethylsiloxane
PE	Plyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene
PR	Productivity rate
PS	Polystyrene
PVC	Polyvinyl chloride
PVDC	Polyvinylidene chloride

PVOH	Polyvinyl alcohol
R	Statistical measure of dispersion
RDF	Residue derived fuel
RE	Recycling efficiency
SCW	Separately collected waste
SFA	Substance flow analysis
SiOx	Silicon oxide
SWC	Separate waste collection
ULDPE	ultra low density polyethylene

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A. Transfer Coefficient Calculation for MFA

Stoffbilanz Kunststoffrecyclinganlage Linie 1 / Berechnung Transferkoeffizienten

Legende
- (rot) Keine Daten verfügbar. Expertenschätzung < 1t/a. Null gesetzt.
- 123456 Keine Daten verfügbar. Expertenschätzwert verwendet.

Nr.	Prozess	Nr.	Input	Menge in t/a	Nr.	Herkunft Input	Nr.	Output	Menge in t/a	Nr.	Zielort Output	Transferkoeffizient
Teilbilanz Linie 1 - Automatische Sortierung												
1.1.0	Inputlager Linie 1 Automatische Sortierung	131	gemischte Kunststoffabfälle	14 171	A0	Kunststofflager	42	gemischte Kunststoffabfälle	14 171	1.1.1	Manuelles Lösen der Ballenbänder	1
1.1.1	Manuelles Lösen der Ballenbänder	42	gemischte Kunststoffabfälle	14 171	1.1.0	Inputlager Linie 1 Automatische Sortierung	44	Draht	49	A1	Schrottcontainer	0,003457766
							43	gemischte Kunststoffabfälle	14 122	1.1.2	Zerkleinerer	0,996542234
1.1.2	Zerkleinerer L1 AS	43	gemischte Kunststoffabfälle	14 122	1.1.1	Manuelles Lösen der Ballenbänder	45	zerkleinerte Kunststoffabfälle	14 122	1.1.3	Überbandmagnet	1
1.1.3	Überbandmagnet	45	zerkleinerte Kunststoffabfälle	14 122	1.1.2	Zerkleinerer L1 AS	46	Eisenmetallschrott	0	A3	Restmüll	0
							47	zerkleinerte Kunststoffabfälle	14 122	1.1.4	Rüttelsieb	1
1.1.4	Rüttelsieb	47	zerkleinerte Kunststoffabfälle	14 122	1.1.3	Überbandmagnet	133	zerkleinerte Kunststoffabfälle < 30mm	0	A4	Reject	0
							48	zerkleinerte Kunststoffabfälle > 30mm	14 122	1.1.5	NIR-Sortierung 1	1
1.1.5	NIR-Sortierung 1	48	zerkleinerte Kunststoffabfälle > 30mm	14 122	1.1.4	Rüttelsieb	49	aussortierte Störstoffe / thermische Fraktion	1 711	A2	Ballenpresse	0,121158476
							50	vorsortierte Kunststoffabfälle > 30mm	12 411	1.1.6	NIR-Sortierung 2	0,878841524
1.1.6	NIR-Sortierung 2	50	vorsortierte Kunststoffabfälle > 30mm	12 411	1.1.5	NIR-Sortierung 1	52	aussortierte Störstoffe / thermische Fraktion	1 711	A2	Ballenpresse	0,137861574
							51	vorsortierte Kunststoffabfälle > 30mm	10 700	1.2.5	Absinkbecken	0,862138426
Teilbilanz Linie 1 - Manuelle Sortierung												
1.2.0	Inputlager Linie 1 Manuelle Sortierung	132	gemischte Kunststoffabfälle	3 742	A0	Kunststofflager	53	gemischte Kunststoffabfälle	3 742	1.2.1	Manuelles Lösen der Ballenbänder	
1.2.1	Manuelles Lösen der Ballenbänder	53	gemischte Kunststoffabfälle	3 742	1.2.0	Inputlager Linie 1 Manuelle Sortierung	134	Draht	13	A1	Schrottcontainer	0,003474078
							54	gemischte Kunststoffabfälle	3 729	1.2.2	Ballenaufreißer	0,996525922
1.2.2	Ballenaufreißer	54	gemischte Kunststoffabfälle	3 729	1.2.1	Manuelles Lösen der Ballenbänder	55	gemischte Kunststoffabfälle	3 729	1.2.3	Manuelle Sortierung	1
1.2.3	Manuelle Sortierung	54	gemischte Kunststoffabfälle	3 729	1.2.2	Ballenaufreißer	56	aussortierte Störstoffe/thermische Fraktion	274	A2	Ballenpresse	0,073478144
							57	vorsortierte Kunststoffabfälle	3 455	1.2.4	Zerkleinerung	0,926521856
1.2.4	Zerkleinerung L1 MS	57	vorsortierte Kunststoffabfälle	3 455	1.2.3	Manuelle Sortierung	58	zerkleinerte Kunststoffabfälle	3 455	1.2.5	Absinkbecken	1
Teilbilanz Linie 1 - Behandlung												
1.2.5	Absinkbecken	50	vorsortierte Kunststoffabfälle > 30mm	10 700	1.1.6	NIR-Sortierung 2	59	Schwergut / Störstoffe	224	A3	Restmüll	0,015824797
		57	vorsortierte Kunststoffabfälle	3 455	1.2.4	Zerkleinerung L1 MS	60	Restmüll / Schlamm	51	A3	Restmüll	0,003602967
		109	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	61	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.6	Mühle	0,980572236
							60	*Prozesswasser*	*0*	*W3*	*Mühlenabwasserbecken 1*	0
1.2.6	Mühle	61	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.5	Absinkbecken	62	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.7	Reinigungszentrifugen	1
1.2.7	Reinigungszentrifugen	62	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.6	Mühle	64	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.8	Waschsilo	1
		110	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	*63*	*Prozesswasser*	*0*	*W3*	*Mühlenabwasserbecken 1*	
1.2.8	Waschsilo	64	vorsortierte Kunststoffabfälle > 30mm	13 880	1.2.7	Reinigungszentrifugen	66	gewaschene Kunststoffabfälle	13 880	1.2.9	Mischbütte 1	1
							65	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitung*	
1.2.9	Mischbütte 1	66	gewaschene Kunststoffabfälle	13 880	1.2.8	Waschsilo	67	gewaschene Kunststoffabfälle	13 880	1.2.10	Hydrozyklonbatterie 1	1
		102	*Prozesswasser*	*0*	*W5*	*Frischwasserbecken*						
1.2.10	Hydrozyklonbatterie 1	67	gewaschene Kunststoffabfälle	13 880	1.2.9	Mischbütte 1	68	Schwergut / Störstoffe	2 776	1.2.13	Hydrozyklonbecken	0,2
		111	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	70	gewaschene Kunststoffabfälle	11 104	1.2.11	Mischbütte 2	0,8
							69	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitung*	

1.2.11	Mischbütte 2	70	gewaschene Kunststoffabfälle	11 104	1.2.10 Hydrozyklonbatterie 1	71	gewaschene Kunststoffabfälle	11 104	1.2.12	Hydrozyklonbatterie 2	1
		101	*Prozesswasser*	*0*	*W5 Frischwasserbecken*						
1.2.12	Hydrozyklonbatterie 2	71	gewaschene Kunststoffabfälle	11 104	1.2.11 Mischbütte 2	73	Schwergut / Störstoffe	1 110	1.2.13	Hydrozyklonbecken	0,1
		112	*Prozesswasser*	*0*	*W1 Reinwasserbecken*	72	sortierte, gewaschene Kunststoffabfälle	9 994	1.2.18	Entwässerungssieb Gutstoff	0,9
						74	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitung*	
1.2.13	Hydrozyklonbecken	68	Schwergut / Störstoffe	2 776	1.2.10 Hydrozyklonbatterie 1	76	Störstoffe Leicht	1 474	1.2.14	Hydrozyklonbatterie 3	0,379374228
		73	Schwergut / Störstoffe	1 110	1.2.12 Hydrozyklonbatterie 2	75	metallische Störstoffe / Restmüll	438	A3	Restmüll	0,112597777
		84	Schwergut / Störstoffe	0	1.2.14 Hydrozyklonbatterie 3	78	Schwergut / Störstoffe / Reject	1 974	1.2.15	Entwässerungssieb Schlechtstoff	0,508027995
		85	*Prozesswasser*	*0*	*1.2.17 Entwässerungssieb Gutstoff*	77	Schlamm	0	A3	Restmüll	0
1.2.14	Hydrozyklonbatterie 3	18	Schwergut / Störstoffe / Reject	0	3.11 Pumpenbecken	84	Schwergut / Störstoffe	0	1.2.13	Hydrozyklonbecken	0
		76	Störstoffe Leicht	1 474	1.2.13 Hydrozyklonbecken	83	sortierte, gewaschene Kunststoffabfälle	1 474	1.2.17	Entwässerungssieb Gutstoff	1
1.2.15	Entwässerungssieb Schlechtstoff	21	Schwergut / Störstoffe / Reject	137	3.12 Paddelbecken 1	80	Schwergut / Störstoffe / Reject	2 521	1.2.16	Schneckenpresse Schlechtstoff	1
		24	Schwergut / Störstoffe / Reject	137	3.13 Zentrifuge 1	79	*Prozesswasser*	*0*	*W5*	*Frischwasserbecken*	
		26	Schwergut / Störstoffe / Reject	137	3.15 Paddelbecken 2						
		28	Schwergut / Störstoffe / Reject	137	3.16 Zentrifuge 2						
		78	Schwergut / Störstoffe / Reject	1 974	1.2.13 Hydrozyklonbecken						
1.2.16	Schneckenpresse Schlechtstoff	80	Schwergut / Störstoffe / Reject	2 412	1.2.15 Entwässerungssieb Schlechtstoff	82	trockene Schwergut / Störstoffe / Reject	2 412	A4	Reject	1
						81	*Prozesswasser*	*0*	*W5*	*Frischwasserbecken*	
1.2.17	Entwässerungssieb Gutstoff	72	sortierte, gewaschene Kunststoffabfälle	9 994	1.2.12 Hydrozyklonbatterie 2	86	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.18	Trockenzentrifuge	1
		83	sortierte, gewaschene Kunststoffabfälle	1 474	1.2.14 Hydrozyklonbatterie 3	85	*Prozesswasser*	*0*	*1.2.13*	*Hydrozyklonbecken*	
1.2.18	Trockenzentrifuge	86	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.17 Entwässerungssieb Gutstoff	88	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.19	Schneckenpresse Gutstoff	1
						87	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitung*	
1.2.19	Schneckenpresse Gutstoff	88	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.18 Trockenzentrifuge	90	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.20	Thermische Trocknung	1
						89	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitung*	
1.2.20	Thermische Trocknung	90	sortierte, gewaschene Kunststoffabfälle	11 468	1.2.19 Schneckenpresse Gutstoff	91	Feuchte Luft	940	U	Umgebung	0,081967213
						92	trockene, sortierte Kunststoffabfälle	10 528	1.2.21	Extruder L1	0,918032787
1.2.21	Extruder L1	92	trockene, sortierte Kunststoffabfälle	10 528	1.2.20 Thermische Trocknung	94	Rückspülungen + Filteraustrag	839	A5	Gitterbox Filteraustrag	0,074162468
		96	Virginmaterial Borealis	253	L Lager	## 93	Teeröl / Kondensat Abgas	1	A6	Auffangbehälter Teeröl	8,83939E-05
		98	Masterbatch Black	80	L Lager	## 130	Metallabfälle / Filter	0,0	A1	Schrottcontainer	0
		99	Zudosieren Sonstiges	298	L Lager	##					
		100	Zudosieren Intern	154	L Lager	##					
		97	*Prozesswasser*	*0*							
						95	Output L1 Kunststoffgranulat	10 473	L3	Silolager	0,925749138

Stoffbilanz Kunststoffrecyclinganlage Linie 3 / Berechnung Transferkoeffizienten

Nr.	Prozess	Nr.	Input	Menge in t/a	Nr.	Herkunftsort	Nr.	Output	Menge in t/a	Nr.	Zielort	Transferkoeffizient
3.0	Inputlager Linie 3 Manuelle Sortierung	0	gemischte Kunststoffabfälle	9553	A0	Kunststofflager	1	gemischte Kunststoffabfälle	9553	3.1	Manuelles Lösen der Ballenbänder	1
3.1	Manuelles Lösen der Ballenbänder	1	gemischte Kunststoffabfälle	9553	3.0	Inputlager Linie 3 Manuelle Sortierung	3	Draht	45	A1	Schrottcontainer	0,004710562
							2	gemischte Kunststoffabfälle	9508	3.2	Ballenaufreißer	0,995289438
3.2	Ballenaufreißer	2	gemischte Kunststoffabfälle	9508	3.1	Manuelles Lösen der Ballenbänder	4	gemischte Kunststoffabfälle	9508	3.3	Manuelle Sortierung	1
3.3	Manuelle Sortierung	4	gemischte Kunststoffabfälle	9508	3.2	Ballenaufreißer	6	aussortierte Störstoffe/thermische Fraktion	1279	A2	Ballenpresse	0,1345183
							5	vorsortierte Kunststoffabfälle	8229	3.4	Vorzerkleinerung	0,8654817
3.4	Vorzerkleinerung	5	vorsortierte Kunststoffabfälle	8229	3.3	Manuelle Sortierung	7	vorsortierte Kunststoffabfälle	8229	3.5	Trommelsieb / Rundlaufsieb	1
3.5	Trommelsieb / Rundlaufsieb	7	vorsortierte Kunststoffabfälle	8229	3.4	Vorzerkleinerung	8	vorsortierte Kunststoffabfälle > 30 mm	8229	3.6	Absinkbecken	1
							9	vorsortierte Kunststoffabfälle < 30 mm	0	A4	Reject	0
3.6	Absinkbecken	8	vorsortierte Kunststoffabfälle > 30 mm	8229	3.5	Trommelsieb / Rundlaufsieb	12	Schwergut / Störstoffe	11	A3	Restmüll	0,001336736
		108	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	11	Restmüll / Schlamm	38	A3	Restmüll	0,004617815
							10	vorsortierte Kunststoffabfälle > 30 mm	8180	3.7	Mühle	0,994045449
							11	*Prozesswasser*	*0*	*MW2*	*Mühlenabwasserbecken L3*	
3.7	Mühle	10	vorsortierte Kunststoffabfälle > 30 mm	8180	3.6	Absinkbecken	13	vorsortierte Kunststoffabfälle > 30 mm	8180	3.8	Reinigungszentrifugen	1
3.8	Reinigungszentrifugen	13	vorsortierte Kunststoffabfälle > 30 mm	8180	3.7	Mühle	14	vorsortierte Kunststoffabfälle > 30 mm	8180	3.9	Kontaktgebläse	1
							15	*Prozesswasser*	*0*	*MW2*	*Mühlenabwasserbecken L3*	
3.9	Kontaktgebläse	14	vorsortierte Kunststoffabfälle > 30 mm	8180	3.8	Reinigungszentrifugen	16	vorsortierte Kunststoffabfälle > 30 mm	8180	3.10	Waschsilo	1
3.10	Waschsilo	16	vorsortierte Kunststoffabfälle > 30 mm	8180	3.9	Kontaktgebläse	17	vorsortierte Kunststoffabfälle > 30 mm	8180	3.11	Pumpenbecken	1
		113	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	*128*	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitg.*	
3.11	Pumpenbecken	17	vorsortierte Kunststoffabfälle > 30 mm	8180	3.10	Waschsilo	3 18	Schwergut / Störstoffe / Reject	0	1.2.14	Hydrozyklonbatterie 3	0
							19	gewaschene Kunststoffabfälle > 30 mm	8180	3.12	Paddelbecken 1	1
3.12	Paddelbecken 1	19	gewaschene Kunststoffabfälle > 30 mm	8180	3.11	Pumpenbecken	1 21	Schwergut / Störstoffe / Reject	136,75	1.2.15	Entwässerungssieb Schlechtstoff	0,016717604
		114	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	20	gewaschene Kunststoffabfälle > 30 mm	8043,25	3.13	Zentrifuge 1	0,983282396
3.13	Zentrifuge 1	20	gewaschene Kunststoffabfälle > 30 mm	8043,25	3.12	Paddelbecken 1	2 24	Schwergut / Störstoffe / Reject	136,75	1.2.15	Entwässerungssieb Schlechtstoff	0,017001834
							22	gewaschene Kunststoffabfälle > 30 mm	7906,5	3.14	Pumpe	0,982998166
							23	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitg.*	
3.14	Pumpe	22	gewaschene Kunststoffabfälle > 30 mm	7906,5	3.13	Zentrifuge 1	25	gewaschene Kunststoffabfälle > 30 mm	7906,5	3.15	Paddelbecken 2	1
3.15	Paddelbecken 2	25	gewaschene Kunststoffabfälle > 30 mm	7906,5	3.14	Pumpe	3 26	Schwergut / Störstoffe / Reject	136,75	1.2.15	Entwässerungssieb Schlechtstoff	0,017295896
		115	*Prozesswasser*	*0*	*W1*	*Reinwasserbecken*	27	sortierte, gewaschene Kunststoffflakes >30mm	7769,75	3.16	Zentrifuge 2	0,982704104

3.16	Zentrifuge 2	27	sortierte, gewaschene Kunststoffflakes >30mm	7769,75	3.15	Paddelbecken 2	4	28	Schwergut / Störstoffe / Reject	136,75	1.2.15	Entwässerungssieb Schlechtstoff	0,017600309
								29	sortierte, gewaschene Kunststoffflakes >30mm	7633	3.17	Gebläse	0,982399691
								30	*Prozesswasser*	*0*	*W4*	*Physikalische Abwasseraufbereitg.*	
3.17	Gebläse	29	sortierte, gewaschene Kunststoffflakes >30mm	7633	3.16	Zentrifuge 2		31	sortierte, gewaschene Kunststoffflakes >30mm	7633	3.18	Thermische Trocknung	1
3.18	Thermische Trocknung	31	sortierte, gewaschene Kunststoffflakes >30mm	7633	3.17	Gebläse		32	Feuchte Luft	382	U	Umgebung	
								33	getrocknete, sortierte Kunststoffflakes > 30 mm	7251,0	3.19	Extruder L3	0,949954146
3.19	Extruder L3	33	getrocknete, sortierte Kunststoffflakes > 30 mm	7251	3.18	Thermische Trocknung		35	Rückspülungen + Filteraustrag	243,0	A5	Gitterbox Filteraustrag	0,033512619
		37	Virginmaterial Borealis	473,0	L	Lager	#	34	Teeröl / Kondensat Abgas	1,0	A6	Auffangbehälter Teeröl	0,000137912
		38	*Prozesswasser*	*0,0*				129	Metallabfälle / Filter	0,0	A1	Schrottcontainer	
		39	Masterbatch Black	4,6	L	Lager	#						
		40	Zudosieren Sonstiges	111,0	L	Lager	#						
		41	Zudosieren Intern	76,5	L	Lager	#						
								36	Output L3 Kunststoffgranulat	7672,1	L3	Silolager	0,969176741

B. Sample Catalogue of 2D Material.

Nr	ID	Description	Mass	Category 1	Category 2	In	Out
1	B1	Cereal Packaging inner layer	5,3	Primary food packaging	Dry food		
2	B2	Butter Madeleines	4,6	Primary food packaging	Bakery products		
3	B3	Toys	10,3	Primary product packaging	Toys	PP	PP
4	B4	Clothing bag	164,3	Primary product packaging	Household products	PE	PE
5	B5	Package of an apple turnover	4,6	Primary food packaging	Bakery products	PP	PP
6	B6	Manner Zarties Milky Vanilla	14,1	Primary food packaging	Snack uncoated	PE	PET
7	B7	Debreziner Spicy	7	Primary food packaging	Meat	PE	PE
8	B8	Cereal Bag inner layer	5,9	Primary food packaging	Dry food	PE	PP
9	B9	Ölz Mini Bussi Hazelnut	5,3	Primary food packaging	Bakery products	PP	PP
10	B10	Debreziner Spicy	6,9	Primary food packaging	Meat		
11	B11	Wachauer smoked pork belly	3,8	Primary food packaging	Meat		
12	B12	Berger ham foil	2,9	Primary food packaging	Meat	PE	PE
13	B13	Berger ham tray	11,6	Primary food packaging	Meat	PE	PA
14	B14	Mozzarella Light	3	Primary food packaging	Dairy	PE	PA
15	B15	Wachauer Knacker	5	Primary food packaging	Meat	PE	PA
16	B16	Ja natürlich breakfast bacon	2,9	Primary food packaging	Meat	PE	?
17	B17	Brioche plait	11,2	Primary food packaging	Bakery products	PP	?
18	B18	Scandinavian smoked salmon	2,9	Primary food packaging	Meat		
19		Scandinavian smoked salmon tray	17,4	Primary food packaging	Meat		
20		Manner coconut waffels	16,3	Primary food packaging	Snack uncoated		
21	B19	Bell´arom Gold coffee	10,5	Primary food packaging	Coffee	PE	PP
22	B20	Omas Backstube Linzerstangerl	3,7	Primary food packaging	Bakery products	PP	PP
23		Lamb's lettuce	2,8	Primary food packaging	Fresh produce		
24	B21	Plastic bag	5,9	Bags	Carrier bags	PE	PE
25		Almdudler Sixpack Wrapping	18,4	Secondary food packaging	Beverages / extra wrapping		
26	B22	Organic fine oat flakes	6,8	Primary food packaging	Dry food	PE	PE
27		Organic Kiwis	3,3	Primary food packaging	Fresh produce		
28		Wiesenthaler Frankfurter	5,7	Primary food packaging	Meat		
29		Sixpack Wrapping bottles	16,6	Secondary food packaging	Beverages / extra wrapping		
30		Fanta Sixpack Wrapping	18	Secondary food packaging	Beverages / extra wrapping		
31	B23	Ferrara Spaghetti	3,1	Primary food packaging	Dry food	PP	PP
32	B24	Spar ready-to-bake pizza dough	6,4	Primary food packaging	Frozen food / convenience	PE	PET
33	B25a	Sbudget Pizza Dairy	6,2	Primary food packaging	Dairy	PE	PA
34	B25b	Milbona Emmentaler	4,3	Primary food packaging	Dairy		
35	B26	Omas Backstube red currant bakery	3,1	Primary food packaging	Bakery products	PP	PP
36		Farmer Ham Tray	15,9	Primary food packaging	Meat		
37		Farmer Ham Foil	4,1	Primary food packaging	Meat		
38	B27	Tomato mix	2,6	Primary food packaging	Fresh produce	PP	PP
39	B28	Gutes vom Bäcker Doughnuts	5,9	Primary food packaging	Bakery products	PP	PP
40		Transparent plastic bag	4,3	Secondary product packaging	Mail order		
41		Tante Fanny pizza dough	8,9	Primary food packaging	Frozen food / convenience		
42		Paprika Tricolore	3,7	Primary food packaging	Fresh produce		
43		Lidl Organic waste bag	4,5	Bags	Bags		
44		Plastic packaging of spare part	3,3	Primary product packaging	Household products		
45		Snack cucumbers	2,1	Primary food packaging	Fresh produce		
46		Bofrost deep-freezing bag	4,6	Primary food packaging	Frozen food / convenience		
47	B29	Transparent plastic bag	17,7	Bags	Carrier bags	PE	PE
48	B30	Hofer carrier bag	173,7	Bags	Carrier bags	PET	PP
49		Cherry tomatoes	3,5	Primary food packaging	Fresh produce		
50	B31	Salty sticks	9,1	Primary food packaging	Snack metallised	PE	PET
51		Protective packaging	189,1	Secondary product packaging	Mail order		
52	B32	Toppitz zipper bag	7	Primary food packaging	Household packaging	PE	PE
53		Small plastic bag for snacks	3,5	Primary food packaging	Household packaging		
54	B33	Small plastic bag for snacks	6,6	Primary food packaging	Household packaging	PE	PE
55		Plastic wrap	4,4	Primary food packaging	Household packaging		
56	B34	Veggini Nuggets	1,8	Primary food packaging	Frozen food / convenience	PP	PET?
57		Small plastic bag for snacks	5,2	Primary food packaging	Household packaging		
58	B35	Protective packaging	18	Secondary product packaging	Mail order	PP	PP
59		Clothing bag	15,9	Primary product packaging	Household products		
60	B36	Clothing bag	15,8	Primary product packaging	Household products	PP	PP
61		Cereal Packaging inner layer	5,3	Primary food packaging	Dry food		
62		Thin plastic tube	1,2	Secondary product packaging	Mail order		
63		Thin plastic tube	1,8	Secondary product packaging	Mail order		
64		Ölz mini cinnamon buns	9,2	Primary food packaging	Bakery products		
65		Plastic bag	13,9	Primary product packaging	Household products		
66		Soda water sixpack wrapping	18,9	Secondary food packaging	Beverages / extra wrapping		
67		Gift wrapping	5,4	Secondary product packaging	Gift wrapping		
68	B37	Resch und Frisch Kornspitz	7,3	Primary food packaging	Bakery products	PP	PP
69	B38	Amazon mailing pouch	14,4	Secondary product packaging	Mail order	PE	PE
70		Plastic pouch	7,6	Primary product packaging	Household products		
71		Meisterbäcker gluten-free bread	9,3	Primary food packaging	Bakery products		
72		Sack of apples	14,9	Primary food packaging	Fresh produce		
73		S Budget Sixpack Beverages	13,2	Secondary food packaging	Beverages / extra wrapping		

74	Thin plastic tube	4,9	Secondary product packaging	Mail order		
75	Plastic bag	4,1	Bags	Bags		
76 B39	Thurner Brioche plaite	5,2	Primary food packaging	Bakery products	PE	PA
77 B40	Salad hearts	3,9	Primary food packaging	Fresh produce	PP	PP
78	Small plastic bag for snacks	5,3	Primary food packaging	Household packaging		
79	Mini Linzerringerl	5,3	Primary food packaging	Bakery products		
80 B41	Spar carrots	6,5	Primary food packaging	Fresh produce	PE	PE
81 B42	S Budget bread cubes	10,1	Primary food packaging	Bakery products	PP	PP
82	Dobble 360	51,6	Primary product packaging	Toys		
83 B43	Lego brick bag	1,7	Primary product packaging	Toys	PP	PP
84	Transport foil	2,8	Secondary product packaging	Mail order		
85	Good Choice Rohkost salad mix	4,5	Primary food packaging	Fresh produce		
86	Lego Sackerl	3,7	Primary product packaging	Toys		
87	Cosy toilet paper packaging	12,5	Primary product packaging	Sanitary products		
88	Lego brick bag	4,7	Primary product packaging	Toys		
89 B44	Bubble wrap	5,8	Secondary product packaging	Mail order	PE	PE
90	Lego brick bag	6,4	Primary product packaging	Toys		
91	Lego brick bag	6,9	Primary product packaging	Toys		
92	Waldquelle Sixpack Wrapping	14,9	Secondary food packaging	Beverages / extra wrapping		
93	Saliva Ejectors Sack	6,5	Primary product packaging	Sanitary products		
94	Lego brick bag	1,2	Primary product packaging	Toys		
95	Zipper bag	9,9	Primary food packaging	Household packaging		
96 B45	Organic bag for fresh produce	1,8	Primary food packaging	Fresh produce	PE	PE
97	Transparent plastic bag	9,5	Secondary product packaging	Mail order		
98 B46	Thin plastic tube	2,7	Secondary product packaging	Mail order	PP	PP
99	Clever deep-freeze baguette	6,8	Primary food packaging	Frozen food / convenience		
100	Clever deep-freeze baguette	7,4	Primary food packaging	Frozen food / convenience		
101	Champignons	4	Primary food packaging	Fresh produce		
102	Lego Sackerl	1,2	Primary product packaging	Toys		
103	Berger cutlett	16	Primary food packaging	Meat		
104 B47	Ölz butter toast	6,2	Primary food packaging	Bakery products	PP	PP
105	Clever Toast Dairy	2	Primary food packaging	Dairy		
106	Transparent plastic bag	4,6	Primary food packaging	Household packaging		
107	Small plastic bag for snacks	0,9	Primary food packaging	Household packaging		
108	Lego brick bag	5,1	Primary product packaging	Toys		
109	Clever deep-freeze baguette	6,7	Primary food packaging	Frozen food / convenience		
110	Plastic bag	2,7	Primary food packaging	Household packaging		
111	Deep-freeze bag 3 liters	4,1	Primary food packaging	Household packaging		
112	Jomo marble cake	7,1	Primary food packaging	Bakery products		
113 B48	Small plastic bag for snacks	1,5	Primary food packaging	Household packaging	PE	PE
114	Small plastic bag for snacks	1,8	Primary food packaging	Household packaging		
115	Small plastic bag for snacks	1,5	Primary food packaging	Household packaging		
116	Small plastic bag for snacks	1,5	Primary food packaging	Household packaging		
117	Berger barbecue sausages	11,2	Primary food packaging	Meat		
118	Lego brick bag	5,7	Primary product packaging	Toys		
119	Lego brick bag	3,8	Primary product packaging	Toys		
120	Lego brick bag	5,5	Primary product packaging	Toys		
121 B49	Bubble wrap	2,5	Secondary product packaging	Mail order	PE	PE
122 B50	HP Color Choice Toner	12,7	Primary product packaging	Household products	PP	PP
123	Snack Day salted chips	9,9	Primary food packaging	Snack metallised		
124 B51	Clever salty sticks	5,8	Primary food packaging	Snack uncoated	PP	?
125	Thin plastic tube	1,6	Bags	Bags		
126	Transparent plastic bag	14,5	Primary food packaging	Household packaging		
127	Spitz wafers	7,1	Primary food packaging	Snack metallised		
128	Clever salty sticks	4,9	Primary food packaging	Snack uncoated		
129	Hygienic sheets	5,2	Primary product packaging	Household products		
130	Toys	6,4	Primary product packaging	Toys		
131	Sixpack Wrapping PET bottles	14,7	Secondary food packaging	Beverages / extra wrapping		
132	Zipper bag	2,8	Primary food packaging	Household packaging		
133	Platic bag	2,7	Primary food packaging	Household packaging		
134	Wrapping of kitchen roll	16,2	Primary product packaging	Sanitary products		
135 B52	Der Gelbe Sack	60,9	Bags	Bags		
136	Zipper bag	3,4	Primary food packaging	Household packaging		
137	Fanta Sixpack Wrapping	9,1	Secondary food packaging	Beverages / extra wrapping		
138 B53	Ikea zipper bag	4,2 g	Primary food packaging	Household packaging	?	PET
139	Roast Master Espresso	22,6 g	Primary food packaging	Coffee		
140	Ölz All Saint's brioche plait	7,2 g	Primary food packaging	Bakery products		
141	Post mailing pouch	1,5 g	Secondary product packaging	Mail order		
142	Bubble wrap	28,5 g	Secondary product packaging	Mail order		
143	LDPE Sack	6,9 g	Bags	Bags		
144	Tork wrapping of toilet paper	46,7 g	Primary product packaging	Sanitary products		
145 B53a	Milka chocolate	1,5 g	Primary food packaging	Snack uncoated		
146	Ölz All Saint's brioche plait	7,8 g	Primary food packaging	Bakery products		
147	Small plastic bag for snacks	1 g	Primary product packaging	Household products		
148	Small plastic bag for snacks	0,9 g	Primary product packaging	Household products		

149	B54	Sbudget ready-to-bake buns	11,3 g	Primary food packaging	Bakery products	PE/PP	PA/PP
150	B55	Transparent sheet	5,9 g	Primary product packaging	Household products	PP	PP
151		Post mailing pouch	3,6 g	Secondary product packaging	Mail order		
152		Gift wrapping	33,6 g	Secondary product packaging	Gift wrapping		
153	B56	Cling film	337,2 g	Secondary product packaging	Mail order	PE	PE
154	B57	Carrier film	17,8 g	Foils	Foils	PDMS	?
155	B58	Snipes shopping bag	30,2 g	Bags	Bags	PE	PE
156		Christmas present	0,7 g	Primary food packaging	Bakery products		
157		Milka chocolate	1,5 g	Primary food packaging	Snack uncoated		
158	B59	Plastic bag	45,8 g	Bags	Bags	PP	PP
159	B60	Piece of generic foil	2 g	Foils	Foils	PP	PP
160	B61	Transparent plastic bag	4,2 g	Bags	Bags	PE	PE
161	B62	Transparent plastic bag	5,4 g	Bags	Bags	PE	PE
162	B63	Transparent plastic bag	1,4 g	Foils	Foils	PE/PP	PE/PP
163	B64	NKD shopping bag	5,1 g	Bags	Carrier bags	PE	PE
164		Post mailing pouch	4,7 g	Secondary product packaging	Mail order		
165	B65	Post mailing pouch	4,7 g	Secondary product packaging	Mail order	PP	PP
166		Sixpack Wrapping PET bottles	7,3 g	Secondary food packaging	Beverages / extra wrapping		
167	B66	Klarsichtsack	4,3 g	Bags	Bags	PE	PE
168	B67	Weihnachtsfolie	3,1 g	Secondary product packaging	Gift wrapping	?	?
169		Transparent plastic bag	4 g	Bags	Bags		
170	B68	Morawa mailing pouch	14,2 g	Secondary product packaging	Mail order	PE/PP	PE/PP
171	B69	FFP2 face mask packaging	2,6 g	Primary product packaging	Sanitary products		
172	B70	Landhof Cabanossi	7,1 g	Primary food packaging	Meat	PE	PET
173	B71	PP foil	1,2 g	Foils	Foils	PP	PP
174		Instant Noodles	4,2 g	Primary food packaging	Snack metallised		
175		Christmas wrapping	6,2 g	Foils	Foils		
176	B72	ekz foil	8,5 g	Foils	Foils	PE	PE
177	B73	Book wrapping film	2,1 g	Foils	Foils	PP	PP
178	B74	Plastic bag	5,7 g	Bags	Bags	PE	PE
179		Plastic bag	3 g	Bags	Bags		
180		Plastic bag	6 g	Bags	Bags		
181		Post mailing pouch	3,5 g	Secondary product packaging	Mail order		
182	B75	Cellophan gift wrapping	8,5 g	Foils	Foils	PP	PP
183	B76	Plastic bag	1,3 g	Bags	Bags	PE	PE
184		Plastic bag	6,2 g	Bags	Bags		
185		Plastic bag	4,4 g	Bags	Bags		
186		PP foil	1,2 g	Foils	Foils		
187		Plastic bag	3,6 g	Bags	Bags		
188		Plastic bag	7,9 g	Bags	Bags		
189		Plastic bag	6,8 g	Bags	Bags		
190	B77	Packaging of a ball-and-socket joint	44,9 g	Primary product packaging	Construction / workshop	PP	PP
191	B78	Foil	99,7 g	Foils	Foils	PE	PE
192		Zipper bag	3,9 g	Primary food packaging	Household packaging		
193	B79	Filter sand packaging	85,1 g	Primary product packaging	Construction / workshop	PE	PE
194		Tie rod packaging	3,9 g	Primary product packaging	Construction / workshop		
195		Tie rod packaging	4,6 g	Primary product packaging	Construction / workshop		
196		Transverse control arm packaging	45,5 g	Primary product packaging	Construction / workshop		
197	B80	Mailing pouch	114,1 g	Secondary product packaging	Mail order	PE	PE
198		Zipper bag	3,9 g	Primary food packaging	Household packaging		
199		Zipper bag	3,9 g	Primary food packaging	Household packaging		
200	B81	Foam inserts for mailing	9,9 g	Secondary product packaging	Mail order	PE	PE
201		Zipper bag	1,4 g	Primary food packaging	Household packaging		
202	B82	Lagerhaus wrapping film	514,5 g	Primary product packaging	Construction / workshop	PE	PE
203		Gelber Sack	69,3 g	Bags	Bags		
204		Black plastic bag	66,8 g	Bags	Bags		
205	B83	Blue plastic bag	22,4 g	Bags	Bags	PE	PE
206		Wrapping of tissue paper	3,5 g	Primary product packaging	Sanitary products		
207		Coca Cola sixpack wrapping	17,6 g	Secondary food packaging	Beverages / extra wrapping		
208	B84	Dreamies	20,3 g	Primary product packaging	Wet pet food	PE	PET
209	B85	Cirkel Backstore shopping bag	34,1 g	Bags	Carrier bags	PE	PE
210		Sbudget toast	6,3 g	Primary food packaging	Bakery products		
211		Crave Protein Strips	6,8 g	Primary product packaging	Dry pet food		
212		Scotty Knabbersticks	7,1 g	Primary product packaging	Dry pet food		
213		Lovely toilet paper wrapping	15,3 g	Primary product packaging	Sanitary products		
214		Lovely toilet paper wrapping	34,7 g	Primary product packaging	Sanitary products		
215		Salted Soletti Fischis	2,2 g	Primary food packaging	Snack metallised		
216		Cosy toilet paper wrapping	14,1 g	Primary product packaging	Sanitary products		
217		Plastic bag	3,7 g	Bags	Bags		
218		Wrapping of tissue paper	3,4 g	Primary product packaging	Sanitary products		
219		Wrapping of tissue paper	3,5 g	Primary product packaging	Sanitary products		
220		Waldquelle sixpack wrapping	45,9 g	Secondary food packaging	Beverages / extra wrapping		
221		Plastiksackerl	11,7 g	Bags	Bags		
222		Cosy toilet paper wrapping	15,8 g	Primary product packaging	Sanitary products		
223	B86	Spar shopping bag	28,2 g	Bags	Carrier bags	PE	PET
224		Green plastic bag	8,5 g	Bags	Bags		

225	B87	Gackerl Sackerl	4,5 g	Bags	Bags	PE	PE
226		Oreo Double Creme	1,7 g	Primary food packaging	Snack metallised		
227		Knorr instant soup	36,1 g	Primary food packaging	Snack metallised		
228		Crunchips Western Style	7,4 g	Primary food packaging	Snack metallised		
229		Thin plastic tube	4,9 g	Bags	Bags		
230		Sbudget carotts	5,5 g	Primary food packaging	Fresh produce		
231	B88	Coushion mailing wrap	15,4 g	Secondary product packaging	Mail order	PE	PE
232	B89	Eco plastic bag	3,6 g	Bags	Bags	PET/PA	PET/PA
233		Meat sandwich	7,7 g	Primary product packaging	Wet pet food		
234		Strawberry pudding	2,7 g	Primary food packaging	Frozen food / convenience		
235		Plastic bag	8 g	Bags	Bags		
236		Pet food with fish and chicken stripes	6,9 g	Primary product packaging	Wet pet food		
237		Felix cat food	3,4 g	Primary product packaging	Wet pet food		
238		Penny toilet paper	12,8 g	Primary product packaging	Sanitary products		
239	B90	Nimm2 Lachgummi	3,6 g	Primary food packaging	Snack uncoated	PP	PP
240		Fizzers double pack	1,1 g	Primary food packaging	Snack uncoated		
241		Mini Burgerpatties	4,9 g	Primary product packaging	Wet pet food		
242		Plastic bag	6,3 g	Bags	Bags		
243		Plastic bag	7,3 g	Bags	Bags		
244		Fake Snickers	5,7 g	Primary food packaging	Snack metallised		
245		Plastic bag	19,5 g	Bags	Bags		
246		Sixpack Wrapping PET bottles	28,9 g	Secondary food packaging	Beverages / extra wrapping		
247		Spar Premium bread rolls	4,7 g	Primary food packaging	Bakery products		
248		Semolina pancake	8,8 g	Primary food packaging	Frozen food / convenience		
249	B91	HDPE plastic bag	4,6 g	Bags	Bags	PP	PP
250		Chewing bars	10,2 g	Primary product packaging	Dry pet food		
251		Cauliflower wrapping	3,4 g	Primary food packaging	Fresh produce		
252		Bubble wrap	72,3 g	Secondary product packaging	Mail order		
253		Koshida cat food	72,4 g	Primary product packaging	Wet pet food		
254		Sbudget smoked salmon	10,3 g	Primary food packaging	Meat		
255	B92	Milka Noisette	2,2 g	Primary food packaging	Snack metallised	PE	PET
256		Bubble wrap	16,8 g	Secondary product packaging	Mail order		
257		Bubble wrap	46,2 g	Secondary product packaging	Mail order		
258		Shopping bag	14,8 g	Bags	Carrier bags		
259	B93	Vegetable packaging	16,5 g	Primary food packaging	Fresh produce	PE	PE/PET
260		Milka	2,6 g	Primary food packaging	Snack metallised		
261		Turkey lamb gourmet dinner	2,9 g	Primary product packaging	Wet pet food		
262		Almdudler Sixpack Wrapping	22,1 g	Secondary food packaging	Beverages / extra wrapping		
263	B94	Chicken Wings BBQ	11,7 g	Primary food packaging	Frozen food / convenience	PE	PP
264		Pommes rustic	11,5 g	Primary food packaging	Frozen food / convenience		
265	B95	Steakhouse pommes	11,8 g	Primary food packaging	Frozen food / convenience	PE	?
266		Wrapping of toilet paper	15,7	Primary product packaging	Sanitary products		
267		Deep-freeze chives	6,4 g	Primary food packaging	Frozen food / convenience		
268	B96	Berger ham	5,5 g	Primary food packaging	Meat	PE	?
269		Topix cat food	24,6 g	Primary product packaging	Dry pet food		
270		Cosy wrapping of toilet paper	15,4 g	Primary product packaging	Sanitary products		
271		Engelbert Strauss clothing sack	11,6 g	Primary product packaging	Household products		
272		Red grape sixpack wrapping	8,4 g	Secondary food packaging	Beverages / extra wrapping		
273		Spitz wafers	6,7 g	Primary food packaging	Snack metallised		
274		Green metal packaging	5,1 g	Primary food packaging	Meat		
275		Milka	4,1 g	Primary food packaging	Snack uncoated		
276		Gelber Sack	72 g	Bags	Bags		
277		Mignon wafers	5,7 g	Primary food packaging	Snack metallised		
278		Snacky Stars	5,8 g	Primary food packaging	Snack metallised		
279		Shopping bag	3,8 g	Bags	Carrier bags		
280		Emmentaler pre-cut	2 g	Primary food packaging	Dairy		
281	B97	Waldviertler potatoes	21,2 g	Primary food packaging	Fresh produce	PE	PE
282		Ölz walnut pastry	4,4 g	Primary food packaging	Bakery products		
283		Berger shopping bag	15 g	Bags	Carrier bags		
284	B98	Fruity Snakes	3,5 g	Primary food packaging	Snack uncoated	PP	PE
285		Shopping bag	11,7 g	Bags	Carrier bags		
286		Meat packaging	5,9 g	Primary food packaging	Meat		
287	B99	Metro product foil	3,1 g	Bags	Carrier bags	PP	PP
288		Bakery product foil	4,8 g	Primary food packaging	Bakery products		
289		Thin plastic tube	4,9 g	Bags	Bags		
290	B100	Mailing pouch	1,8 g	Secondary product packaging	Mail order	PP	PP
291	B101	Snack peppers	2,1 g	Primary food packaging	Fresh produce	PP	PP
292		Clear film	5,7 g	Foils	Foils		
293	B102	Post mailing pouch	3,3 g	Secondary product packaging	Mail order	PP	PP
294	B103	Lagerhaus animal food packaging	129,7 g	Primary product packaging	Dry pet food	PE	PET
295		Cat food sachets	402,4 g	Primary product packaging	Wet pet food		
296		Plastic bag	6,1 g	Bags	Bags		
297		Ham	2,9 g	Primary food packaging	Meat		
298		Ja natürlich breakfast bacon	5,4 g	Primary food packaging	Meat		
299		Tempo wrapping of tissue paper	7,3 g	Primary product packaging	Sanitary products		
300		Soft Snack	8 g	Primary food packaging	Snack uncoated		

301		Berger ham	2,9 g	Primary food packaging	Meat		
302		Gelber Sack	71,1 g	Bags	Bags		
303		Almond flour	3,6 g	Primary food packaging	Dry food		
304		Airwaves wrapping	1,7 g	Primary food packaging	Snack uncoated		
305		Lidl Brioche	11,2 g	Primary food packaging	Bakery products		
306		Gelber Sack	74,5 g	Bags	Bags		
307		Almond flour	3,3 g	Primary food packaging	Dry food		
308		Omas Backstube Linzerstangerl	3,7 g	Primary food packaging	Bakery products		
309		Juice pouch	13,5 g	Bags	Bags		
310		Bon Prix shopping bag	27,6 g	Bags	Carrier bags		
311		Berger garlic roast	2 g	Primary food packaging	Meat		
312		Plastic bag	6 g	Bags	Carrier bags		
313		Ikea zipper bag	5,7 g	Primary food packaging	Household packaging		
314		Bubble wrap	15,7 g	Secondary product packaging	Mail order		
315		Berger cutlett	13,1 g	Primary food packaging	Meat		
316	B104	Ginger Bisquits	0,9 g	Primary food packaging	Bakery products	PP	PP
317		Lidl Ribiselaugen	3 g	Primary food packaging	Bakery products		
318		Haribo Goldbären	3,5 g	Primary food packaging	Snack uncoated		
319	B105	Farmers Country pistacchios	8,7 g	Primary food packaging	Dry food	PP	PP
320		Ginger Bisquits	11 g	Primary food packaging	Bakery products		
321		Manner wafers vanilla flavor	17 g	Primary food packaging	Bakery products		
322		Dumpling with fish stuffing	3,9 g	Primary food packaging	Frozen food / convenience		
323		Shopping bag	4,9 g	Bags	Carrier bags		
324		Anker white bread	5,9 g	Primary food packaging	Bakery products		
325	B106	Solo hygienic sheets	7,1 g	Primary product packaging	Sanitary products	PE	PET
326		Manner wafers coconut flavor	14,4 g	Primary food packaging	Bakery products		
327		Lego brick bag	2	Primary product packaging	Toys		
328		Berger pork meat	13,9 g	Primary food packaging	Meat		
329		S Budget Gouda	2,3 g	Primary food packaging	Dairy		
330	B107	Bauernland Erdäpfeltaler	12,3 g	Primary food packaging	Frozen food / convenience	PE	PE
331	B108	Wrapping of Disney bed linen	25,5 g	Primary product packaging	Household products	PP	PP
332	B109	W5 all-purpose cleaning sheets	5,9 g	Primary product packaging	Sanitary products	PE	PET
333		Wrapping of Disney bed linen	23 g	Primary product packaging	Household products		
334		Lidl Brioche	11,3 g	Primary food packaging	Bakery products		
335		Lego brick bag	4,2 g	Primary product packaging	Toys		
336		Sixpack Wrapping PET bottles	12 g	Secondary food packaging	Beverages / extra wrapping		
337		Deep-freeze bag	6,5 g	Primary food packaging	Household packaging		
338		Shopping bag	5,6 g	Bags	Carrier bags		
339		Kinder Schokobons	8,1 g	Secondary food packaging	Beverages / extra wrapping		
340		Lidl Ribiselaugen	3,3 g	Primary food packaging	Bakery products		
341		Linzerstangerl	4,2 g	Primary food packaging	Bakery products		
342		Wrapping of Looney Toons bed linen	17,8	Primary product packaging	Household products		
343		Sixpack Wrapping PET bottles	20,7 g	Secondary food packaging	Beverages / extra wrapping		
344		Cereal Packaging inner layer	6,2 g	Primary food packaging	Dry food		
345		Lego brick bag	3,1 g	Primary product packaging	Toys		
346		Eightpack Wrapping PET bottles	18,1 g	Secondary food packaging	Beverages / extra wrapping		
347		Organic breakfast beacon	2,8 g	Primary food packaging	Meat		
348	B110	Haribo Almdudler	3,1 g	Primary food packaging	Snack uncoated	PP	PP
349		Spar Butter Madeleines	5 g	Primary food packaging	Bakery products		
350	B111	Crepes	3,2 g	Primary food packaging	Bakery products	PE	PP
351		Lego brick bag	2,6 g	Primary product packaging	Toys		
352	B112	Thin plastic tube	1,8 g	Primary food packaging	Bakery products	PP	PP
353		Wrapping of PET bottle3s	4,8 g	Secondary food packaging	Beverages / extra wrapping		
354		Spar Soda water sixpack wrapping	19,6 g	Secondary food packaging	Beverages / extra wrapping		
355		Clear film	15,2 g	Foils	Foils		
356		Shopping bag	5,7 g	Bags	Carrier bags		
357		Shopping bag	4,9 g	Bags	Carrier bags		
358		Clear film	6,2 g	Foils	Foils		
359	B113	Packaging of a curtain	14,9 g	Primary product packaging	Household products	PP	PP
360		Lego brick bag	4,5 g	Primary product packaging	Toys		
361		Lego brick bag	1 g	Primary product packaging	Toys		
362		Lego brick bag	3,8 g	Primary product packaging	Toys		
363		Thin plastic tube	1,9 g	Primary food packaging	Bakery products		
364		Spar Butter Madeleines	4,7 g	Primary food packaging	Bakery products		
365		Blue Star WC stone sleeve	4,3 g	Secondary product packaging	Wrapping		
366		Clear film	4 g	Foils	Foils		
367		Sbudget pears	6,3 g	Primary food packaging	Fresh produce		
368		Berger beef schnitzel	24,6 g	Primary food packaging	Meat		
369		Turbo briquettes	28,2 g	Primary product packaging	Construction / workshop		
370		Turbo briquettes	27,9 g	Primary product packaging	Construction / workshop		
371		Turbo briquettes	36,7 g	Primary product packaging	Construction / workshop		
372		Turbo briquettes	28,1 g	Primary product packaging	Construction / workshop		
373	B114	Turbo briquettes	28,8 g	Primary product packaging	Construction / workshop	PE	PE
374	B115	Recheis egg pasta	35,2 g	Primary food packaging	Dry food	PE	PE
375		Perfect Fit cat food	18,2 g	Primary product packaging	Wet pet food		
376		Knorr basis for soups	4,8 g	Primary food packaging	Frozen food / convenience		

377		Bergader cheese	2,4 g	Primary food packaging	Dairy		
378		Turbo briquettes	18,7 g	Primary product packaging	Construction / workshop		
379	B116	Mens knee-highs	12,3 g	Primary product packaging	Household products	PE	PE
380		AluFix deep-freezing bag	6,5 g	Primary food packaging	Household packaging		
381		plastic bag	1,8 g	Primary food packaging	Household packaging		
382		Tante Fanny Croissant	5,5 g	Primary food packaging	Frozen food / convenience		
383		Spar marble cake	6,4 g	Primary food packaging	Frozen food / convenience		
384		Ham	9,6 g	Primary food packaging	Meat		
385	B117	Schärdinger Traungold	5,7 g	Primary food packaging	Dairy	PE	PET
386		Schärdinger Traungold	6,4 g	Primary food packaging	Dairy		
387		AluFix deep-freezing bag	6,1 g	Primary food packaging	Household packaging		
388		AluFix deep-freezing bag	14,4 g	Primary food packaging	Household packaging		
389		Gift wrapping	17,8 g	Secondary product packaging	Gift wrapping		
390		Spar Butter Toast	5,6 g	Primary food packaging	Bakery products		
391		Gelber Sack	71,8 g	Bags	Bags		
392		Lego brick bag	10,4 g	Primary product packaging	Toys		
393		Lego brick bag	34,6 g	Primary product packaging	Toys		
394		Spar deep-freezing bag	4,8 g	Primary food packaging	Household packaging		
395		Zipper bag	5,7 g	Primary food packaging	Household packaging		
396		Toppitz plastic bag	6,4 g	Primary food packaging	Household packaging		
397		Mens knee-highs	12,5 g	Primary product packaging	Household products		
398		Tante Fanny Croissant	5,7 g	Primary food packaging	Frozen food / convenience		
399		Stasnik Kantwurst	10,8 g	Primary food packaging	Meat		
400		Resch und Frisch Kornstangerl	7,2 g	Primary food packaging	Bakery products		
401	B118	Sportgummi	4,2 g	Primary food packaging	Snack uncoated	PP	PP
402		breaded fish	21,1 g	Primary food packaging	Meat		
403		Turbo briquettes	27,8 g	Primary product packaging	Construction / workshop		
404		Turbo briquettes	29,9 g	Primary product packaging	Construction / workshop		
405		Turbo briquettes	27,8 g	Primary product packaging	Construction / workshop		
406		Turbo briquettes	28,2 g	Primary product packaging	Construction / workshop		
407		Turbo briquettes	32,2 g	Primary product packaging	Construction / workshop		
408		Turbo briquettes	29,3 g	Primary product packaging	Construction / workshop		
409		Turbo briquettes	29,2 g	Primary product packaging	Construction / workshop		
410		Turbo briquettes	27,8 g	Primary product packaging	Construction / workshop		
411		Turbo briquettes	27,9 g	Primary product packaging	Construction / workshop		
412		Turbo briquettes	28 g	Primary product packaging	Construction / workshop		
413		Turbo briquettes	28,3 g	Primary product packaging	Construction / workshop		
414		Turbo briquettes	28,5 g	Primary product packaging	Construction / workshop		
415		Turbo briquettes	29,7 g	Primary product packaging	Construction / workshop		
416		Turbo briquettes	29,6 g	Primary product packaging	Construction / workshop		
417		Turbo briquettes	28,6 g	Primary product packaging	Construction / workshop		
418		Turbo briquettes	32,5 g	Primary product packaging	Construction / workshop		
419		Turbo briquettes	29,7 g	Primary product packaging	Construction / workshop		
420		plastic bag	7,1 g	Bags	Carrier bags		
421		Zipper bag	7 g	Primary food packaging	Household packaging		
422		Arlberger Bergwurzn	7,8 g	Primary food packaging	Meat		
423		Tante Fanny Croissant	7,7 g	Primary food packaging	Frozen food / convenience		
424		Knorr Basis Pasta Asciutta	4,6 g	Primary food packaging	Frozen food / convenience		
425		Bella baking chocolate	4 g	Primary food packaging	Snack uncoated		
426		Resch und Frisch Kornstangerl	2,2 g	Primary food packaging	Bakery products		
427		Spar napkin dumplings	15,8 g	Primary food packaging	Frozen food / convenience		
428		Polar Frost meat dumplings	14,3 g	Primary food packaging	Frozen food / convenience		
429		Sbudget pizza cheese	6,5 g	Primary food packaging	Dairy		
430		Chicken	4,1 g	Primary food packaging	Meat		
431		Spar potatoes	12,5 g	Primary food packaging	Fresh produce		
432		AluFix deep-freezing bag	3,4 g	Primary food packaging	Household packaging		
433		Lego brick bag	4,8 g	Primary product packaging	Toys		
434		Gusto Puffuletti	9 g	Primary food packaging	Snack uncoated		
435		Recheis Spaghetti	4,4 g	Primary food packaging	Dry food		
436		Ich bin Österreich toast ham	10,8 g	Primary food packaging	Meat		
437		Thurner Brioche plaite	6,1 g	Primary food packaging	Bakery products		
438		Gelber Sack	78,9 g	Bags	Bags		
439		Spätzle	8,7 g	Primary food packaging	Frozen food / convenience		
440		Deep-freezing bag	8,7 g	Primary food packaging	Household packaging		
441		Chicken legs	14,9 g	Primary food packaging	Meat		
442		Hofstätter Frankfurter	5,8 g	Primary food packaging	Meat		
443		Deep-freezing bag	6,1 g	Primary food packaging	Household packaging		
444		Lego brick bag	7,7 g	Primary food packaging	Snack metallised		
445		Good Choice salad mix	4,7 g	Primary food packaging	Fresh produce		
446		Lovely wrapping of toilet paper	16,6 g	Primary product packaging	Sanitary products		
447		Plastic bag for fresh produce	5,1 g	Primary food packaging	Fresh produce		
448		Transparent film	3,3 g	Primary product packaging	Household products		
449		Good Choice salad mix	3,8 g	Primary food packaging	Fresh produce		
450		Spätzle	10,2 g	Primary food packaging	Frozen food / convenience		
451		Pancakes	14,4 g	Primary food packaging	Frozen food / convenience		
452		Resch und Frisch Kornstangerl	15,2 g	Primary food packaging	Bakery products		

453		Plastic bag for fresh produce	7,3 g	Primary food packaging	Fresh produce		
454		Deep-freezing bag	7,6 g	Primary food packaging	Household packaging		
455		Spar parsley	5,5 g	Primary food packaging	Fresh produce		
456		Spar peppers	3,6 g	Primary food packaging	Fresh produce		
457		Happy Harvest bread rolls	14,1 g	Primary food packaging	Bakery products		
458		Billa Curly Fries	12,8 g	Primary food packaging	Frozen food / convenience		
459		Bubble wrap	22,8 g	Secondary product packaging	Mail order		
460		Solo kitchen roll	19,3 g	Primary product packaging	Sanitary products		
461		Lego brick bag	8,8 g	Primary product packaging	Toys		
462		Lego brick bag	2,7 g	Primary product packaging	Toys		
463		Lego brick bag	3,5 g	Primary product packaging	Toys		
464		Tassimo coffee big pack	14 g	Primary food packaging	Coffee		
465		Gelber Sack	69,8 g	Bags	Bags		
466		Green Fruit Enoki Mushrooms	1,2 g	Primary food packaging	Fresh produce		
467		Thurner Brioche plaite	4,9 g	Primary food packaging	Bakery products		
468		Green Fruit Enoki Mushrooms	1,3 g	Primary food packaging	Fresh produce		
469		Transparent plastic bag	2,6 g	Bags	Bags		
470		Terra sweet potato chips	9,9 g	Primary food packaging	Frozen food / convenience		
471		Wiesbauer Gipfelstangerl	4,9 g	Primary food packaging	Meat		
472		Lego brick bag	7,8 g	Primary product packaging	Toys		
473		Billa almonds	1,9 g	Primary food packaging	Dry food		
474	B119	Coca Cola mini can wrapping	8,5 g	Secondary food packaging	Beverages / extra wrapping	PE	PE
475		Thurner Brioche plaite	5,1 g	Primary food packaging	Bakery products		
476		Alpenhof pork roast	10 g	Primary food packaging	Meat		
477		Spar Natur Pur lettuce	4,7 g	Primary food packaging	Fresh produce		
478		Plastic bag	3,4 g	Primary food packaging	Household packaging		
479		Spar deep-freezing bag	3,4 g	Primary food packaging	Household packaging		
480		Bon Appetit ready-to-bake baguettte	11,8 g	Primary food packaging	Bakery products		
481	B120	Neuburger cuts	4,5 g	Primary food packaging	Meat		
482		Kellys Chips Hashtagchips	3,4 g	Primary food packaging	Snack metallised		
483		Kriegshammer turnips	2,4 g	Primary food packaging	Fresh produce		
484		Spar marble cake	5,8 g	Primary food packaging	Snack metallised		
485	B121	Austrian peter root	3,4 g	Primary food packaging	Fresh produce	PE	PP
486		Organic pepper	5 g	Primary food packaging	Fresh produce		
487	B122	Obi Shopping bag	20,6 g	Bags	Carrier bags	PE	PE
488		Müller Shopping bag	23,9 g	Bags	Carrier bags		
489		Kellys Snips	2,7 g	Primary food packaging	Snack metallised		
490	B123	Ja Natürlich bakery	8,3 g	Primary food packaging	Bakery products	PP	PP
491		Plastic bag	5,7 g	Bags	Bags		
492		Gift wrapping goldene foil	1,6 g	Secondary product packaging	Gift wrapping		
493		Al mare smoked salmon	20,4 g	Primary food packaging	Meat		
494		Knabbernossi	2,3 g	Primary food packaging	Meat		
495		Ölz butter toast	4,7 g	Primary food packaging	Bakery products		
496		Kellys popcorn chips	2,7 g	Primary food packaging	Snack metallised		
497		Shah Excellence cat chewing sticks	9 g	Primary product packaging	Wet pet food		
498		Yellow garbage bag	11,6 g	Bags	Bags		
499		Transparent plastic bag	5,7 g	Bags	Bags		
500		Cellophan gift wrapping	2 g	Secondary product packaging	Gift wrapping		
501		Transparent plastic bag	11,2 g	Bags	Bags		
502		Lego brick bag	5,6 g	Primary product packaging	Toys		
503		Lego brick bag	3,7 g	Primary product packaging	Toys		
504		Lego brick bag	5,6 g	Primary product packaging	Toys		
505		Lego brick bag	4,1 g	Primary product packaging	Toys		
506		Lego brick bag	3,6 g	Primary product packaging	Toys		
507		Toys	2,1 g	Primary product packaging	Toys		
508		Disposable gloves	2 g	Primary product packaging	Household products		
509		Deep-freezing bag	2,9 g	Primary food packaging	Household packaging		
510	B124	Kung Fu Panda pudding dessert	0,9 g	Primary food packaging	Snack metallised	PP	PP
511	B125	Nivex green beans	2,1 g	Primary food packaging	Fresh produce	PP	PP
512		Wiesbauer Bergsteiger	11,2 g	Primary food packaging	Meat		
513		Resch und Frisch doughnuts	6,4 g	Primary food packaging	Bakery products		
514		Carrier bags	7,4 g	Bags	Carrier bags		
515		Bag for fresh produce	1,9 g	Primary food packaging	Fresh produce		
516	B126	Rayher modelling clay	6,7 g	Primary product packaging	Toys	PE	PET
517		Transparent bag	2,6 g	Primary food packaging	Household packaging		
518		Pine glas noodles	3,3 g	Primary food packaging	Frozen food / convenience		
519		Spar Premium tomato basil chips	5,8 g	Primary food packaging	Snack metallised		
520		Sinnack whole grain ready-to-bake bred rolls	11,8 g	Primary food packaging	Bakery products		
521		Cosy wrapping of toilet paper	14,3 g	Primary product packaging	Sanitary products		
522		Agnello mangold	5,1 g	Primary food packaging	Fresh produce		
523	B129	Wawi wholemilk couverture	1,2 g	Primary food packaging	Dry food	PP	?
524		Fresh herbs chives	2 g	Primary food packaging	Fresh produce		
525	B128	Airplus bubble wrapping	26,5 g	Secondary product packaging	Mail order	PE	PE
526	B127	Toys	3,7 g	Primary product packaging	Toys	PP	PP
527		Mailing pouch	4,8 g	Secondary product packaging	Mail order		
528		Basil	9,5 g	Primary food packaging	Fresh produce		

529		Deep-freezing bag	4,7 g	Primary food packaging	Household packaging		
530		Deep-freezing bag	2,9 g	Primary food packaging	Household packaging		
531		Cellaric	6 g	Primary food packaging	Fresh produce		
532		Physalis	4,7 g	Primary food packaging	Fresh produce		
533		Spar Natur Pur Kiwis	3 g	Primary food packaging	Fresh produce		
534		Plastic bag	2,5 g	Primary food packaging	Household packaging		
535		Happy Harvest bread rolls	14,5 g	Primary food packaging	Bakery products		
536		Natur organic tomatoes	2,7 g	Primary food packaging	Fresh produce		
537		Lego brick bag	6 g	Primary product packaging	Toys		
538		Plastic bag	8,1 g	Primary food packaging	Household packaging		
539		Glas noodles mungo beans	4 g	Primary food packaging	Dry food		
540		Gärtner Gemüse tomatoes	2,1 g	Primary food packaging	Fresh produce		
541		Ja Natürlich butter spread	2,4 g	Primary food packaging	Dairy		
542		Billa almonds	2,1 g	Primary food packaging	Dry food		
543		Billa almonds	1,7 g	Primary food packaging	Dry food		
544		Cling film	2,9 g	Primary food packaging	Household packaging		
545		Zurück zum Ursprung Kantwurst	2,3 g	Primary food packaging	Meat		
546		Wrapping of napkins	2,7 g	Primary product packaging	Household products		
547		Lego brick bag	3,6 g	Primary product packaging	Toys		
548		Lego brick bag	3,5 g	Primary product packaging	Toys		
549		Clear film	3,3 g	Primary food packaging	Household packaging		
550		Ja Natürlich Bio Alpkönig	10,7 g	Primary food packaging	Dairy		
551		Gärtnerkräuter thyme	3 g	Primary food packaging	Fresh produce		
552		Gärtnerkräuter rosemary	2,5 g	Primary food packaging	Fresh produce		
553		Small plastic bag for snacks	1,4 g	Primary food packaging	Household packaging		
554		Lego brick bag	3,5 g	Primary product packaging	Toys		
555		Gelber Sack	67,7 g	Bags	Bags		
556		Carloni Tortelloni meat	8,7 g	Primary food packaging	Frozen food / convenience		
557		Carloni Torteloni spinach	9,7 g	Primary food packaging	Frozen food / convenience		
558		Shah Excellence cat food	4,1 g	Primary product packaging	Wet pet food		
559		Blue bag	7,4 g	Primary food packaging	Household packaging		
560		Ikea packaging	2 g	Bags	Bags		
561		Ikea packaging	2,4 g	Bags	Bags		
562		Small plastic bag for snacks	4,6 g	Primary food packaging	Household packaging		
563		Small plastic bag for snacks	5,8 g	Primary food packaging	Household packaging		
564		AluFix deep-freezing bag	6,2 g	Primary food packaging	Household packaging		
565		BoFrost pancakes	14,8 g	Primary food packaging	Frozen food / convenience		
566		Babylove Premium diapers	11,9 g	Primary product packaging	Sanitary products		
567		AluFix deep-freezing bag	7,4 g	Primary food packaging	Household packaging		
568		AluFix deep-freezing bag	4,7 g	Primary food packaging	Household packaging		
569		AluFix deep-freezing bag	2,6 g	Primary food packaging	Household packaging		
570		AluFix deep-freezing bag	9,1 g	Primary food packaging	Household packaging		
571		Ikea packaging	4,2 g	Primary product packaging	Household products		
572		Waldquelle Sixpack Wrapping	15,3 g	Secondary food packaging	Beverages / extra wrapping		
573		Transparent bag	6,3 g	Bags	Bags		
574		Pampers wet wipes	7 g	Primary product packaging	Sanitary products		
575		Seiler farmer smoked pork	17,3 g	Primary food packaging	Meat		
576	B128	Wettex	2,1 g	Primary product packaging	Household products	PP	PP
577		Vossen towel	79,6 g	Primary product packaging	Household products		
578	B129	Wieselburger beer can wrapping	15,5 g	Secondary food packaging	Beverages / extra wrapping	PE	PE
579		Aibler oven meat loaf	4,2 g	Primary food packaging	Meat		
580		SunVegs Broccoli	2,4 g	Primary food packaging	Fresh produce		
581		Ikea packaging	2,3 g	Primary product packaging	Household products		
582	B130	Ölz mini cinnamon buns	1,2 g	Primary food packaging	Bakery products	PP	?
583		Transparent bag	5,2 g	Bags	Bags		
584	B131	Frosch detergent	46,6 g	Primary product packaging	Sanitary products	PE	PET
585		Spar steak vegetable mix	8,7 g	Primary food packaging	Frozen food / convenience		
586		Choco chip cookies	4,1 g	Primary food packaging	Bakery products		
587		Backetteria puff pastry	2,1 g	Primary food packaging	Frozen food / convenience		
588		Floralys wrapping of toilet paper	16,7 g	Primary product packaging	Sanitary products		
589	B132	Alpengut Gouda	3,4 g	Primary food packaging	Dairy	PE	PA
590	B133	Cookie bag	4,6 g	Primary food packaging	Bakery products	PP	PET
591		Gelber Sack	66,6 g	Bags	Bags		
592		Spar prosciutto cotta arosto	11,6 g	Primary food packaging	Meat		
593		Plastic bag	3,8 g	Primary food packaging	Household packaging		
594		Mailing bag	4,7 g	Secondary product packaging	Mail order		
595		Ikea packaging	4 g	Primary product packaging	Household products		
596		Amazon mailing pouch	21,8 g	Secondary product packaging	Mail order		
597		Gröbi sixpack wrapping	20,3 g	Secondary food packaging	Beverages / extra wrapping		
598		Gelber Sack	70,8 g	Bags	Bags		
599		Bofrost Kaiserschmarrn	11,4 g	Primary food packaging	Frozen food / convenience		
600		Clear film	6,4 g	Primary product packaging	Household products		
601		Hofer Suprawisch	3,3 g	Primary product packaging	Household products		
602		Ikea packaging	7,3 g	Primary product packaging	Household products		
603	B134	Schär Meisterbäcker Vital	9,1 g	Primary food packaging	Bakery products	PE	PA
604		Sixpack Wrapping PET bottles	9,3 g	Secondary food packaging	Beverages / extra wrapping		

605		Carloni Tortelloni meat	8,9 g	Primary food packaging	Frozen food / convenience		
606		PE bag	4,7 g	Bags	Bags		
607	B135	Nanu Nana shopping bag	8,4 g	Bags	Carrier bags	PE	PE
608		Transport wrapping	154,1 g	Secondary product packaging	Mail order		
609		Push button plastic bag	34,3 g	Primary food packaging	Household packaging		
610		Push button plastic bag	33,6 g	Primary food packaging	Household packaging		
611		Push button plastic bag	34,6 g	Primary food packaging	Household packaging		
612		PE bag	6,6 g	Bags	Bags		
613		Waldquelle sixpack wrapping	14,6 g	Secondary food packaging	Beverages / extra wrapping		
614		Saskia sixpack wrapping	20,3 g	Secondary food packaging	Beverages / extra wrapping		
615		Bubble wrap	21,3 g	Secondary product packaging	Mail order		
616		Bubble wrap	31,1 g	Secondary product packaging	Mail order		
617		Gifting bag	17,2 g	Bags	Bags		
618	B136	Tonibox	7 g	Primary product packaging	Toys	PE	PET
619		Tonibox	7,1 g	Primary product packaging	Toys		
620		Tonibox	6,1 g	Primary product packaging	Toys		
621		Tonibox	7,1 g	Primary product packaging	Toys		
622		Moser Glockner Punkerl	3,9 g	Primary food packaging	Meat		
623	B137	Recheis ABC soup noodles	3,1 g	Primary food packaging	Dry food	PP	PP
624		PE bag	4,6 g	Secondary product packaging	Mail order		
625	B138	Spar mini muffins	8,4 g	Primary food packaging	Bakery products	PP	PP
626		BoFrost Rustikana	10,7 g	Primary food packaging	Frozen food / convenience		
627		Ölz butter toast	6,1 g	Primary food packaging	Bakery products		
628	B139	Dominosteine	1,5 g	Primary food packaging	Bakery products	PP	PP
629		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
630		Spar Natur Pur plastic bag for fresh produce	2,6 g	Primary food packaging	Fresh produce		
631		Tann Knacker	5,7 g	Primary food packaging	Meat		
632	B140	Spar napkin	1,5 g	Primary product packaging	Household products	PP	PP
633		Stork Kaufrüchtchen	4,8 g	Primary food packaging	Snack uncoated		
634	B141	Fizzers Minis	3,4 g	Secondary food packaging	Beverages / extra wrapping	PP	PET
635	B142	Milka Naps	4,4 g	Secondary food packaging	Beverages / extra wrapping	PP	PP
636		Mini Mentos	4,3 g	Secondary food packaging	Beverages / extra wrapping		
637		Handel Tyrol bacon	14,1 g	Primary food packaging	Meat		
638		Neuburger cuts	4,5 g	Primary food packaging	Meat		
639		Soletti Cracker	1,1 g	Primary food packaging	Snack metallised		
640	B143	Berger Frankfurter	15,4 g	Primary food packaging	Meat	PE	PA
641		Spar peppers	3,1 g	Primary food packaging	Fresh produce		
642		Gutes vom Bäcker breakfast croissant	6,1 g	Primary food packaging	Bakery products		
643		Spar chives	2,5 g	Primary food packaging	Fresh produce		
644		Spar Natur Pur carrots	6,4 g	Primary food packaging	Fresh produce		
645		Blumauer cherry tomatoes	2,6 g	Primary food packaging	Fresh produce		
646		Ölz walnut pastry	4,5 g	Primary food packaging	Bakery products		
647		Spar peppers	3,8 g	Primary food packaging	Fresh produce		
648	B144	Small plastic bag for snacks	0,8 g	Primary food packaging	Household packaging	PP	PE
649		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
650		Small plastic bag for snacks	0,9 g	Primary food packaging	Household packaging		
651		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
652		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
653		Small plastic bag for snacks	0,9 g	Primary food packaging	Household packaging		
654		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
655		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
656		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
657		Small plastic bag for snacks	0,9 g	Primary food packaging	Household packaging		
658		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
659		Small plastic bag for snacks	0,9 g	Primary food packaging	Household packaging		
660		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
661		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
662		Small plastic bag for snacks	1,2 g	Primary food packaging	Household packaging		
663		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
664		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
665		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
666		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
667		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
668		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
669		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
670		Small plastic bag for snacks	1,2 g	Primary food packaging	Household packaging		
671		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
672		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
673		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
674		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
675		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
676		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
677		Small plastic bag for snacks	1,2 g	Primary food packaging	Household packaging		
678		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
679		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
680		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		

681		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
682		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
683		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
684		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
685		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
686		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
687		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
688		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
689		Small plastic bag for snacks	1 g	Primary food packaging	Household packaging		
690		Spar deep-freezing bag	3,2 g	Primary food packaging	Household packaging		
691		Transparent film	3,4 g	Foils	Foils		
692		Yellow garbage bag	14,9 g	Bags	Bags		
693		Spar marble cake	6,2 g	Primary food packaging	Bakery products		
694		Thurner Brioche plaite	6,4 g	Primary food packaging	Bakery products		
695		Recheis Fleckerl	6,6 g	Primary food packaging	Dry food		
696		Knorr ABC instant soup	4,9 g	Primary food packaging	Frozen food / convenience		
697		Nivex green beans	3,7 g	Primary food packaging	Fresh produce		
698		transparent bag	6,3 g	Bags	Bags		
699		Clear film	27,8 g	Foils	Foils		
700	B145	Ölz winter cake	4,8 g	Primary food packaging	Bakery products	PP	PP
701		Gelber Sack	87,9 g	Bags	Bags		
702		Roast Master Espresso	23,1 g	Primary food packaging	Coffee		
703		Recheis Sternchen	3 g	Primary food packaging	Dry food		
704		Clear film	27,7 g	Foils	Foils		
705		Post mailing pouch	2,8 g	Secondary product packaging	Mail order		
706		Roast Master Espresso	23,5 g	Primary food packaging	Coffee		
707		Small plastic bag for snacks	1 g	Bags	Bags		
708		Post mailing pouch	2,7 g	Secondary product packaging	Mail order		
709		Cling film	4,1 g	Foils	Foils		
710		Cling film	29,1 g	Foils	Foils		
711		Small plastic bag for snacks	1 g	Bags	Bags		
712		Thin plastic tube	1,2 g	Primary food packaging	Bakery products		
713	B146	Cellophan gift wrapping	3,2 g	Foils	Foils	PP	PP
714		Kelly Original chips	5,9 g	Primary food packaging	Snack metallised		
715		Pombären	2,8 g	Primary food packaging	Snack metallised		
716		Soletti cracker	1,3 g	Primary food packaging	Snack metallised		
717		Ölz winter cake	3,5 g	Primary food packaging	Bakery products		
718		Pepper mix	4,2 g	Primary food packaging	Fresh produce		
719		Blumauer cherry tomatoes	3 g	Primary food packaging	Fresh produce		
720		Red plastic net	1,6 g	Primary food packaging	Fresh produce		
721		Thurner Brioche plaite	3,4 g	Primary food packaging	Bakery products		
722		Post mailing pouch	5,1 g	Secondary product packaging	Mail order		
723	B147	Plastic tube	19,4 g	Secondary product packaging	Mail order	PE	PP
724		Spar deep-freezing bag	4,9 g	Primary food packaging	Household packaging		
725		Sbudget carotts	5,6 g	Primary food packaging	Fresh produce		
726		Lego brick bag	0,6 g	Primary product packaging	Toys		
727		Lego brick bag	1,4 g	Primary product packaging	Toys		
728		Bahlsen cookie bag	1,5 g	Primary food packaging	Bakery products		
729		Bahlsen cookie bag	5,2 g	Primary food packaging	Bakery products		
730		Mailing material	3,7 g	Secondary product packaging	Mail order		
731		Kellys pepper riffle chips	3,6 g	Primary food packaging	Snack metallised		
732		Gutes vom Bäcker cheese kornspitz	5,2 g	Primary food packaging	Bakery products		
733		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
734		Neuburger cuts tray	14,4 g	Primary food packaging	Meat		
735		Small plastic bag for snacks	1,1 g	Primary food packaging	Household packaging		
736		Mailing pouch	3,7 g	Secondary product packaging	Mail order		
737		Mailing pouch	4,8 g	Secondary product packaging	Mail order		
738		Mailing pouch	4,1 g	Secondary product packaging	Mail order		
739		Clear film	4,6 g	Primary food packaging	Household packaging		
740		Gröbi wixpack wrapping	21,3 g	Secondary food packaging	Beverages / extra wrapping		
741		Gifting wrap	11,7 g	Foils	Foils		
742		Soletti Cracker	1,1 g	Primary food packaging	Snack metallised		
743		Clear film	27,5 g	Primary product packaging	Household products		
744		Wolf Eigold egg noodles	4,2 g	Primary food packaging	Dry food		
745		Turkey knacker	3 g	Primary food packaging	Meat		
746		Transparent foil	0,7 g	Primary product packaging	Household products		
747		Transparent foil	0,7 g	Primary product packaging	Household products		
748		Ready-to-eat bread rolls	16,8 g	Primary food packaging	Bakery products		
749		Ready-to-eat bread rolls	16,7 g	Primary food packaging	Bakery products		
750		Good Choice mix salad	4,2 g	Primary food packaging	Fresh produce		
751		Snack Fun chips	9,2 g	Primary food packaging	Snack metallised		
752		Happy Harvest nuts	10,7 g	Primary food packaging	Dry food		
753		transparent bag	50,5 g	Bags	Bags		
754		Super Deal Salami	6 g	Primary food packaging	Meat		
755		Wrapping of toilet paper	19,5 g	Primary product packaging	Sanitary products		
756		Clear film	2,1 g	Foils	Foils		

757	Spar Enjoy bread bag	4,3 g	Primary food packaging	Bakery products		
758	Haribo Balla	3 g	Primary food packaging	Snack uncoated		
759	Soletti salted sticks	6,5 g	Primary food packaging	Snack metallised		
760	Kinder Schokobons	7,4 g	Secondary food packaging	Beverages / extra wrapping		
761	Lego brick bag	4 g	Primary product packaging	Toys		
762	Striezinger chicken breast	2,1 g	Primary food packaging	Meat		
763 B148	Santa claus bag	5,6 g	Primary food packaging	Household packaging	PP	PP
764	Santa claus bag	5,5 g	Primary food packaging	Household packaging		
765	Hofer carotts	5,3 g	Primary food packaging	Fresh produce		
766	Snack Fun Kartoffelsticks	3,3 g	Primary food packaging	Snack metallised		
767	Snack Fun Riffelchips	7,8 g	Primary food packaging	Snack metallised		
768	Hofer carrots	5 g	Primary food packaging	Fresh produce		
769	Soda water sixpack wrapping	18 g	Secondary food packaging	Beverages / extra wrapping		
770	Plastic bag	7,2 g	Bags	Bags		
771	Plastic bag	4,2 g	Bags	Bags		
772	Plastic bag	1,8 g	Bags	Bags		
773	Plastic bag	1,8 g	Bags	Bags		
774	Plastic bag	2,1 g	Bags	Bags		
775	Packaging of bamboo kitchen tools	2,7 g	Primary product packaging	Household products		
776	Folio deep-freezing bag	2,9 g	Primary food packaging	Household packaging		
777	Pears	5,5 g	Primary food packaging	Fresh produce		
778	Green beans	3,8 g	Primary food packaging	Fresh produce		
779	Bella Malmonds	2,4 g	Primary food packaging	Dry food		
780	Spar Cheddar	11,4 g	Primary food packaging	Dairy		
781	Spar Cheddar	1,9 g	Primary food packaging	Dairy		
782	Cookie bag	2,1 g	Primary food packaging	Household packaging		
783	Snack Fun riffle chips	9,4 g	Primary food packaging	Snack metallised		
784	Snacking paper	5,6 g	Foils	Foils		
785	Bon Appetit ready-to-bake baguettte	11,8 g	Primary food packaging	Bakery products		
786 B149	Fair Trade roses	6,1 g	Primary food packaging	Fresh produce	PP	PP
787	Aibler toast ham	6,1 g	Primary food packaging	Meat		
788	Fair Trade roses	6,1 g	Primary food packaging	Fresh produce		
789	Thin plastic tube	1,6 g	Bags	Bags		
790	Cling film	1,7 g	Foils	Foils		
791	Cling film	5,1 g	Foils	Foils		
792	Cereal Packaging inner layer	12,6 g	Primary food packaging	Dry food		
793	Pears	5 g	Primary food packaging	Fresh produce		
794	Spar Natur Pur Kiwis	2,9 g	Primary food packaging	Fresh produce		
795	Transparent bag	4,7 g	Bags	Bags		
796	Sorger Ungharian Salami	2,9 g	Primary food packaging	Meat		
797	Clever Mozzarella grated	6,5 g	Primary food packaging	Dairy		
798	Sbudget smoked salmon	10,9 g	Primary food packaging	Meat		
799	Sorger Ungharian salami	2,3 g	Primary food packaging	Meat		
800	Face mask packaging	5,5 g	Primary product packaging	Sanitary products		
801	Gelber Sack	67,6 g	Bags	Bags		
802	Aibler cuts	5,4 g	Primary food packaging	Meat		
803	Ölz Brioche burger buns	4,1 g	Primary food packaging	Bakery products		
804	Topix cat food	23,8 g	Primary product packaging	Dry pet food		
805	Fair Hof spear ribs	14,2 g	Primary food packaging	Meat		
806	Happy Harvest bread rolls	14,4 g	Primary food packaging	Bakery products		
807	Aibler toast ham	5,9 g	Primary food packaging	Meat		
808	Aibler toast ham	5,5 g	Primary food packaging	Meat		
809	Aibler toast ham	4,8 g	Primary food packaging	Meat		
810	Aibler toast ham	6,5 g	Primary food packaging	Meat		
811	Sbudget snack mix	5,9 g	Primary food packaging	Snack uncoated		
812	Soda water sixpack wrapping	19,6 g	Secondary food packaging	Beverages / extra wrapping		
813	Bon Appetit Aufbackbaguette	12,3 g	Primary food packaging	Bakery products		
814	Dürre with cheese	6,1 g	Primary food packaging	Meat		
815	Fanta sixpack wrapping	16,9 g	Secondary food packaging	Beverages / extra wrapping		
816	Snacking paper	5,4 g	Foils	Foils		
817	Manner lucky charm	2,4 g	Primary food packaging	Snack uncoated		
818	Arlberger Landjäger	5 g	Primary food packaging	Meat		
819	Milfina Mozzarella grated	6,5 g	Primary food packaging	Dairy		
820	Sbudget smoked salmon	10,5 g	Primary food packaging	Meat		
821	Arlberger Landjäger	5 g	Primary food packaging	Meat		
822	Clear film	3 g	Foils	Foils		
823	Kräuerlimo sixpack wrapping	17,9 g	Secondary food packaging	Beverages / extra wrapping		
824	Bella almonds	2,5 g	Primary food packaging	Dry food		
825	Backbox bread bag	8,9 g	Primary food packaging	Bakery products		
826	Organic Corn	3,9 g	Primary food packaging	Fresh produce		
827	Super Deal Salami	6 g	Primary food packaging	Meat		
828	Soda water sixpack wrapping	18 g	Secondary food packaging	Beverages / extra wrapping		
829	Happy Harvest bread rolls	14,4 g	Primary food packaging	Bakery products		
830	Gelber Sack	63,5 g	Bags	Bags		
831	Soda water sixpack wrapping	18,8 g	Secondary food packaging	Beverages / extra wrapping		
832	Fairhof spear ribs	15,2 g	Primary food packaging	Meat		

833	Napkins	3,1 g	Primary product packaging	Household products
834	Parsley	4,5 g	Primary food packaging	Fresh produce
835	Lettuce	5 g	Primary food packaging	Fresh produce
836	Emmentaler cuts	3,1 g	Primary food packaging	Dairy
837	Small plastic bag for snacks	1,5 g	Primary food packaging	Household packaging
838	Gifting wrap	2,1 g	Foils	Foils
839	Tranparent bag	1,6 g	Bags	Bags
840	Transparent foil	1,3 g	Foils	Foils
841	Tranparent bag	0,8 g	Bags	Bags
842	Transparent foil	0,7 g	Primary food packaging	Household packaging
	Total mass	10373,7 g		

Analysed sample

C. Material Composition of Multilayer Objects

Category 1 **Primary food packaging**

Bakery products n = 21

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	1	0	2	0	0	0	0	0
PP	1	14	1	0	0	0	0	0	2
PET	0	1	0	0	0	0	0	0	0
PA	2	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	1	0	0
PA/PP	0	0	0	0	0	1	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	2	0	0	0	0	0	0	0

Meat n = 8

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	2	0	1	3	0	0	0	0	2
PP	0	0	0	0	0	0	0	0	0
PET	1	0	0	0	0	0	0	0	0
PA	3	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	2	0	0	0	0	0	0	0	0

Household packaging n = 6

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	3	1	0	0	0	0	0	0	0
PP	1	1	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	1
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	1	0	0	0	0	0	0

Dairy n = 4

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	1	3	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	1	0	0	0	0	0	0	0	0
PA	3	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Coffee n = 1

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	1	0	0	0	0	0	0	0
PP	1	0	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Fresh produce n = 10

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	3	1	1	0	0	0	0	0	0
PP	1	5	0	0	0	0	0	0	0
PET	1	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Snack metallised n = 3

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	2	0	0	0	0	0	0
PP	0	1	0	0	0	0	0	0	0
PET	2	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Snack uncoated n = 6

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	1	1	0	0	0	0	0	0
PP	1	3	0	0	0	0	0	0	1
PET	1	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	1	0	0	0	0	0	0	0

Frozen food / convenience n = 5

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	1	1	1	0	0	0	0	0	1
PP	1	0	1	0	0	0	0	0	0
PET	1	1	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	1	0	0	0	0	0	0	0	0

Dry food n = 7

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	2	1	0	0	0	0	0	0	0
PP	1	3	0	0	0	0	0	0	1
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	1	0	0	0	0	0	0	0

Category 1 **Primary product packaging**

Construction / workshop n = 4

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	3	0	0	0	0	0	0	0	0
PP	0	1	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Garden n = 0

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Household products n = 9

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	2	0	0	0	0	0	0	0	0
PP	0	7	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Sanitary products n = 3

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	3	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	3	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Toys n = 5

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	2	0	0	0	0	0	0
PP	0	3	0	0	0	0	0	0	0
PET	2	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Wet pet food n = 1

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	1	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	1	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Dry pet food n = 1

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	1	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	1	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Category 1 **Secondary product packaging**

Gift wrapping n = 1

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	1

Mail order n = 15

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	8	1	0	0	0	0	0	0	0
PP	1	5	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	1	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Wrapping n = 0

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Category 1 **Bags and foils**

Carrier bags n = 9

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	6	0	1	0	0	0	0	0	0
PP	0	1	1	0	0	0	0	0	0
PET	1	1	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	0	0	0	0	0

Bags n = 11

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	8	0	0	0	0	0	0	0	0
PP	0	2	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	0
PE/PP	0	0	0	0	0	0	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	1	0
?	0	0	0	0	0	0	0	0	0

Foils n = 9

	PE	PP	PET	PA	PDMS	PE/PP	PA/PP	PET/PA	?
PE	2	0	0	0	0	0	0	0	0
PP	0	5	0	0	0	0	0	0	0
PET	0	0	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	0
PDMS	0	0	0	0	0	0	0	0	1
PE/PP	0	0	0	0	0	1	0	0	0
PA/PP	0	0	0	0	0	0	0	0	0
PET/PA	0	0	0	0	0	0	0	0	0
?	0	0	0	0	1	0	0	0	0