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Characteristics of ‘polybags’ used for low-value consignments in the mail, courier, express and parcel industry

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With the continuous growth of shipment volumes in the courier, express and parcel (CEP) market, mainly driven by e-commerce, the usage of so-called polybags as packaging material for low-value goods is increasingly replacing conventional cardboard boxes or kraft paper envelopes. Especially in the Asian region the usage of polybags as packaging material can be considered as status quo. Despite their advantages regarding costs, durability or tampering protection, the flexible shape and the material properties of polybags lead to major challenges when being processed with automated material handling technology in logistics distribution centers. Depending on one’s point of view the usage of polybags in the CEP industry can be seen as boon or bane. Another dilemma in conjunction with this kind of packaging material is that there is no precise definition of the term polybag neither in literature, nor in the packaging branch or in the CEP industry. This often leads to wrong interpretations and misunderstandings. The aim of this paper is to define polybags based on their physical characteristics and to analyze the behavior of polybags as they can be found in today’s shipments. This paper especially focuses on the evaluation of the limpness/rigidity and the static and dynamic coefficients of friction (COF) of polybags in comparison to cardboard and kraft paper. The paper also discusses other influencing factors such as weight, velocity and lift.

[CEP, polybag, small packet, low-value consignment, mixed mail]

1 INTRODUCTION

The outbreak of COVID19 in December 2019, which initially led to an epidemic in China and then to a pandemic in the course of spring 2020, once more revealed that logistics is a system-relevant economic sector. Today's logistics is characterized by its globally networked supply and value chains, it is highly flexible and complex and thus forms the backbone of modern supply concepts [BH09]. Being a system-critical backbone applies in particular to the field of intralogistics, i.e. the discipline which covers ‘[...] the handling of goods in industry, trade and public institutions’ [Arn06, p. 1]. Due to the lockdowns in almost all countries and the associated measures to contain the pandemic, online trade and e-commerce increased particularly strongly, which also had a direct impact on the courier, express and parcel (CEP) industry. After a continuously growing shipment volume in all areas of the CEP market over the last few years (see Figure 1), the CEP industry in Germany still expected a growth of 3.5 to 7 % in the B2C sector in 2020 [EK20, p. 8], despite the COVID19-induced economic crisis. The latest data from the annual German CEP study even shows a growth of 10.9 % in shipment volume with a new absolute all-time record of a total of 4 billion shipments sent [EK21a, p. 11]. This growth fluctuated significantly in the course of the year 2020. In the first half of the year it was just over 7.4 %, while in the second it was 14.1 % [EK21a, p. 11]. Also the volume of shipments sent during the Christmas season 2020 to end consumers is more than 2.5 times higher compared to the previous year, resulting in 440 million B2C shipments [EK21b, n.p.]. This is not surprising, since the ‘[…] growth of internet shopping has profoundly changed consumer behavior over the past few years’

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[PBG18, p. 301] which has now been additionally sped up by the limitations of local trade due to lockdowns.

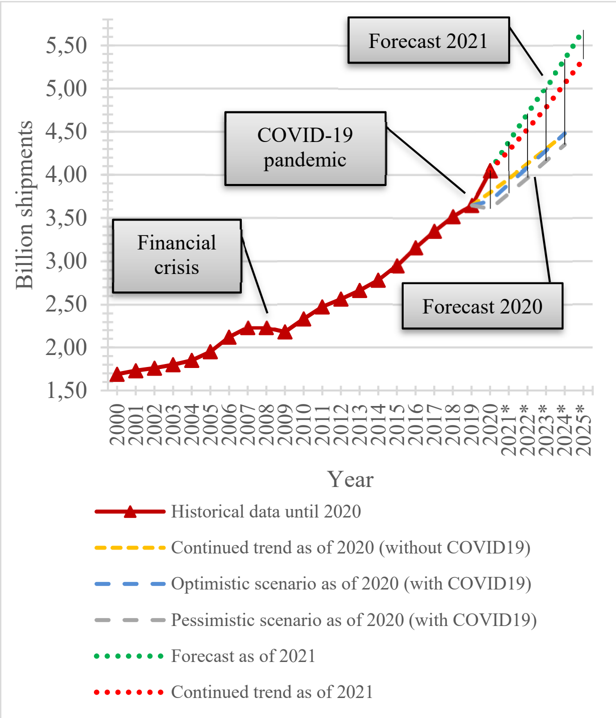

Figure 1. Historical and forecasted data of CEP shipment volumes in Germany until 2025 [cp. EK20, p. 13, EK21a, p. 13]

According to [EK20, pp. 8, 21, EK21a, 12, 21] there is an ongoing shift in market shares between B2B and B2C shipments within the German CEP industry as depicted in Figure 2. ‘For many consumers, the internet is, amongst other things, a powerful new sales channel providing greater choice on what goods and services to purchase and which countries to buy from.’ [PBG18, S. 301]. Buying items from non-domestic shops is also called cross-border purchasing.

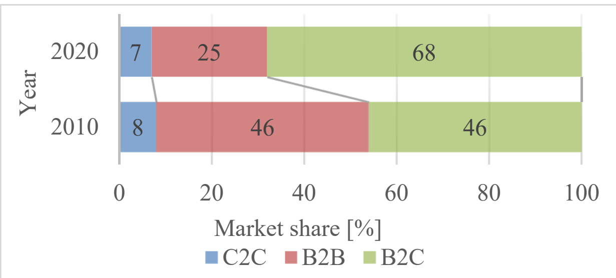

Figure 2. Development of the individual market segments in the national German parcel market [EK21a, p. 21]

Especially Chinese websites are among the most popular destinations for online shoppers in many EU member states [WIK19, p. 42]. With 26 %, China leads the list of the top cross-border destinations for global shoppers, ahead of the US with 21 %, UK/GB with 14 %, Germany with 10 % and Japan with 5 % [Pay18, p. 10]. According to a survey among cross-border e-commerce shoppers by the International Post Corporation (IPC) [Int19, p. 9], the ‘[…] most commonly used e-retailers for the most recent cross-border purchase were Amazon (25 %), Alibaba/AliExpress (20 %), eBay (14 %) and Wish (11 %).’ The survey also shows that China is clearly the primary e-commerce exporter worldwide over the last years, which can be seen in Figure 3. The reasons why consumers prefer to buy items cross-border rather than domestically are different by country and region according to the IPC study [Int19, p. 9] but predominantly, the three most common answers given are:

- price is cheaper abroad (60 %),
- product is not available locally (36 %),
- delivery from abroad is cheap (20 %).

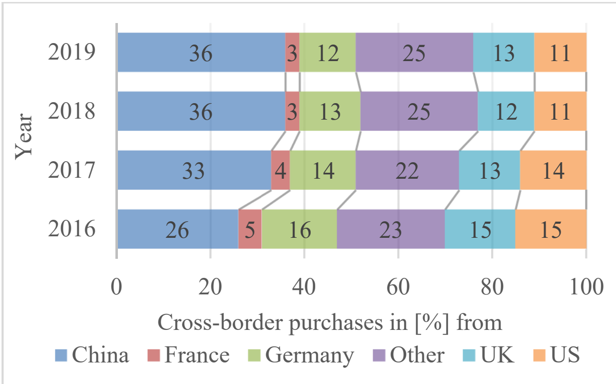

Figure 3. Key export countries for cross-border e-commerce [cp. Int19, p. 12]

The fact that goods can still be offered for less than a local purchase despite international shipping can be explained by several facts. In most cases e-commerce shipments actually have a low shipment value, i.e. the content is of little value (44 % below 25 € [cp. Int19, p. 13]), which further triggers regulatory effects such as Value-Added Tax (VAT) exemptions, if the value is less than 22 €. In order to relieve customs from the burden of checking small packages for potential tax revenues and hence speed up transit of low-value goods being imported into EU member states by mail, there was an optional VAT relief until July 2021. The administrative relief was also known as Low-Value Consignment Relief (LVCR) and was governed by the EU Council Directive 2009/132/EC [Eur09]. By means of the so-called ‘import one stop shop’ (IOSS), a system has now been created whereby additional future formalities with regard to import taxes can be avoided. It can therefore be assumed that the volume of small consignments will not drop significantly as a result of the discontinuation of the VAT relief.

Finally, the terminal dues that are to be paid by postal service providers from emerging countries are relatively low, as defined by the Universal Post Union (UPU). This

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scenario has led to a substantial growth in volumes of small consignments from Asia to EU member states [WIK19, p. 42], as depicted in Figure 4. According to the study by [WIK19], the considered postal e-commerce imports end up at the particular national Universal Service Providers. This is also reflected by the findings of [Int19, p. 13], according to which 86 % of the shipments can be classified under UPU terminology as small packets (part of letter mail rather than parcel service), weighing up to 2 kg.

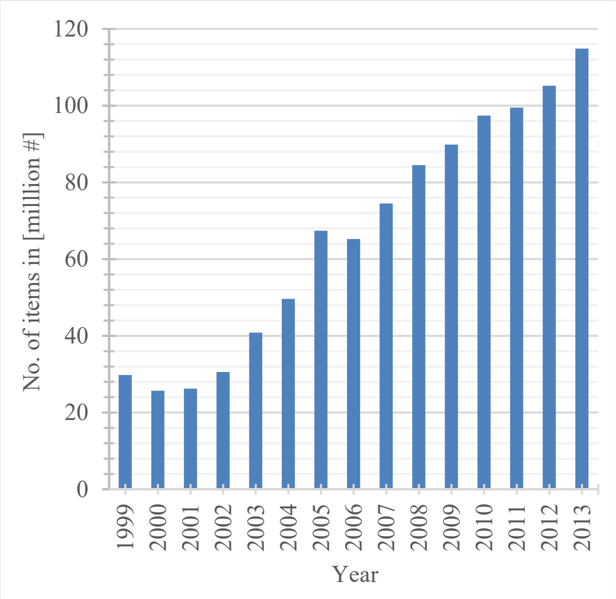

Figure 4. *Total volumes of international small consignments originating from outside the EU [cp. Eur15, p. 37]*

Another study among cross-border shoppers by [Pay18, p. 11] provides potential information on the content of the small consignments by listing the most popular categories for cross-border purchases among all online shoppers surveyed (% of cross-border shoppers in each category):

- clothing, footwear and accessories (68 %),
- consumer electronics, computers, tablets, mobiles and peripherals (53 %),
- toys and hobbies (53 %),
- jewelry/watches (51 %),
- cosmetics/beauty products (46 %),
- collectibles, memorabilia and art (42 %),
- sports and outdoors equipment (40 %).

While materials and types of classic transport packaging in Germany[1] has remained relatively constant in recent years, there is unfortunately little data on the packaging material of small consignments, such as those shown in Figure 5, which are imported into EU member states by mail.

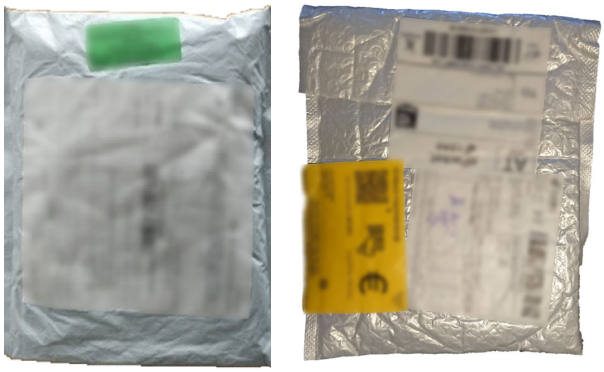

Figure 5. *Low-value consignments (value < 22 €) with green label indicating VAT exemption prior to July 2021 (left side) and with yellow label indicating an consignment with import VAT to be paid by the recipient after July 2021 (right side) [own illustration]*

Obviously, there is a great variety ranging from classic cardboard boxes, to paper-based envelopes (kraft paper) or plastic bags. Only a study on the economic impacts of online consumer sales on additional packaging in Ireland gives a vague idea of the share between the two most prominent materials: cardboard and plastics. In Ireland, on the one hand, cardboard is still the principal type of packaging material accompanying the imported consumer goods but its share has fallen from 80 % in 2015 to 76 % in 2019. On the other hand, the share of all imported packaging materials due to plastics is growing very strongly. Particularly noteworthy is that the volume of imported plastic packaging waste has grown very rapidly by 23 % Cross Annual Growth Rate (CAGR) during 2015-2019, compared with the 17 % CAGR in respect of cardboard, which represents strong growth. [McC19, p. 10–11]

In contrast to cardboard boxes, which generally apply to numerous standards and technical regulations such as [DIN05] for dimensional coordination, there are neither regulations nor definitions for those consignments wrapped in plastic bags. E-commerce consignments including low-value consignments are often neither letters nor normed parcels, and are sometimes called mixed-mail items ([cp. Sie21, p. 4] or small packets[2] ([UW18, p. 27]). In fact, there is even no distinct term in the CEP industry to describe such consignments. A survey conducted among various Designated Postal Operators and Express Mail Services

[1] Market structure of transport packaging in Germany: corrugated cardboard 65.1 %, foils 10.3 %, wood 9.2 %, solid cardboard 9.4 %, plastic packaging material 6.0 % (cp. Ver21, p. 2)

[2] 'Small packets' are letter post items that contain goods.

revealed that these companies use naming schemes that are primarily based on the classification of the individual product portfolio [SP19, p. 50]. Figure 6 shows a tag cloud that represents the variety of different English terms that is used for small packets/low-value consignments either within CEP or packaging industries.

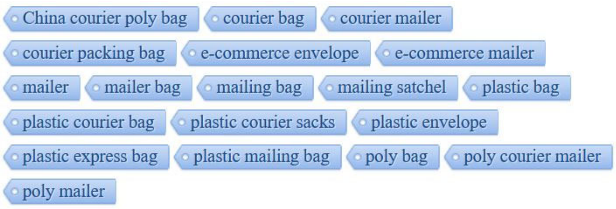

Figure 6. Tag cloud of various terms used to describe packaging material made from plastics for small packets/low-value consignments [own illustration]

Polybag is a suitable umbrella term to describe the type of consignment as it can be seen from several different perspectives. On the one hand 'poly' considers the fact that the bag is made from plastics, as 'poly' is an abbreviation for polythene, which itself is a contraction of polyethylene. The term polybag is commonly used to describe protective covers e.g., glossy magazines in polybag wrapping. Also resellers using the Amazons logistics and fulfillment solution FBA are required to pack certain goods into 'poly bags' made from plastics [Ama17]. On the other hand, it can also be interpreted to represent the Greek word 'poly', meaning 'many, plenty or various' which can also be seen as appropriate, as it considers the enormous variety of bags in terms of material, shape and physical characteristics that can be observed. In the further course of this paper, small consignments of low-value having a wrapping made of plastics are therefore called polybags.[3]

2 Problem statement

The increasing share of B2C shipments described in the previous chapter is having a strong impact on the CEP industry. Nowadays, logistics no longer only connects commercial enterprises, but theoretically all households worldwide [HSD18, p. 247–248]. This circumstance leads to a multiple increase of possible destinations in the logistics networks and makes an automated sorting at high speed and precision necessary. As a result of the large volumes of shipments that must be correctly routed through logistics networks consisting of depots and/or hubs, the CEP industry is constantly placing higher demands on the performance of sorting and distribution systems, which is strongly driving their development. [JH12, p. 7]. Figure 7 shows parts of a typical sorting system as it is often used in a hub or depot.

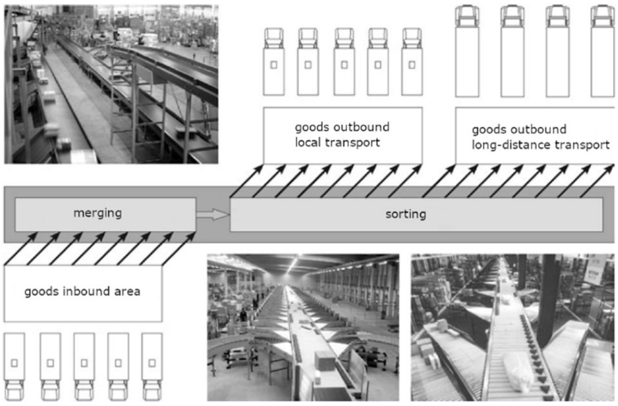

Figure 7. Typical sorter (infeed and distribution conveyor) within the CEP industry [cp. JH12, p. 15]

The logistical performance that needs to be provided by the conveying technology and specialized sorting machinery depends on the volume of shipments (or the size of the distribution center respectively) and the time windows available. In a dispatch depot, the required performance is low at approx. 3,000-7,000 parcels/h, while in a larger hub or a receiving depot, it is high at approximately 16,000 parcels/h. [JH12, p. 9] The development of sorting systems has progressed rapidly in recent years, with newly built distribution centers reaching sorting capacities of 50,000 parcels/h [Wen21, p. 4]. According to [JH12, p. 26] sorting systems can be divided into five different functional areas, each of which combines different functions as shown in Figure 8. Depending on the implementation and the size of the distribution center, the functions can be combined locally or implemented in a different sequence [JH12, p. 25].

The heart of a sorting system is the sorter[4] itself, for which there are many different technical solutions due to the growing and changing requirements. In terms of topology, sorters can be divided into three variants: line, loop and circular sorters. Distribution centers in the CEP industry mainly make use of line and loop sorters. Line sorters can be found where a fixed number of destination relations is typical. The incoming goods are continuously distributed to the end stations and often conveyed directly into the waiting trucks, swap bodies or containers. Loop sorters are used when a more complex routing (e.g. curves, moderate inclines/declines, etc.) or automatic recirculation (read errors, no matching end station, etc.) is required. [JH12, p. 55]

[3] This article considers not only polybags but also bags, envelopes and boxes made from kraft paper and cardboard.

[4] The term 'sorter' strictly speaking means distribution conveyors, both in theory and in practice. This vagueness is due to the difficulty of exact translation of the terms used in German.

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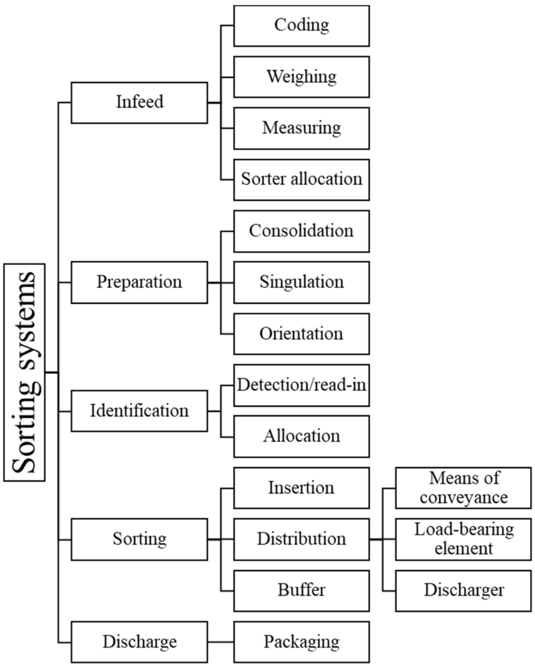

Figure 8. Functions of a sorting system [cp. JH12, p. 26]

The following list shows an excerpt of technical implementations of sorters that often can be found in the mail and CEP industry. In addition, a value range of the achievable nominal throughput (in transport units/hour) taken from literature is added in brackets [cp. JH12, p. 103–105].

- Cross-belt/Double deck sorter (12,000-26,000 TU/h)
- Sliding shoe sorter/Zip sorter (8,000-15,000 TU/h)
- Carrying-shoe sorter (8,000-15,000 TU/h)
- Gull-wing -/ Split-tray -/ Bomb-bay sorter (7,200-10,000 TU/h)
- Tilt-tray sorter (6,000-24,000 TU/h)
- Castor sorter (11,400-12,000 TU/h)
- Rotary/Swivel arm sorter (3,300-6,000 TU/h)

Although some of these sorter types such as the cross-belt or tilt-tray sorter are definitely suitable for sorting polybags by design, substantial operational issues and challenges are being reported from Universal Service Providers [cp. WIK19, p. 42]. The following general physical characteristics of polybags lead to undesired behavior in the logistics process:

- usually limp or (highly) flexible,
- random and variable geometric shape (e.g., contours of the content),
- random and variable position of Center of Gravity (CG),
- small geometric dimensions[5],
- lightweight[6].

When sorting polybags with existing automated material handling equipment, problems related to these characteristics can occur in any of the five functional areas of sorting systems.

1. Infeed

In the CEP industry, shipments are usually delivered by trucks, which are unloaded in different ways depending on the transport container. Trucks, swap bodies or containers that only transport stackable items (like cardboard boxes) are either unloaded manually, with an employee working inside the vehicle and placing the items directly onto a telescopic belt conveyor. Or in the case of more modern hubs the unloading process onto the infeed conveyor can also be semi-[7] or fully automated, which is also called bulk unloading and can be seen in Figure 9. [cp. JH12, p. 26]

Figure 9: 'Rapid unloader' developed by the company PHS[8] and in service at the Austrian Post as an example for fully automatic unloading of parcels in bulk mode [cp. LWF17, p. 232]

[5] As reference values, those for small packets according to the UPU specification in Article 17-104 can be considered. These are: minima: surface < 90 x 140 mm, maxima: length, width and depth combined: 900 mm, with greatest dimension < 600 mm. In practice, however, the shipment sizes differ from these. [Int18, Volume II - 139]

[6] In general, a few hundred grams or even less (see also Figure 15 and Figure 16), but not exceeding 2 kg according to the UPU specification for small packets [cp. UW18, p. 27].

[7] An exemplary machine for semi-automatic unloading is the BEUMER Parcel Picker.

[8] https://www.phsolutions.at/

‘Mixed mail is typically delivered in bulk as a loose load in roll cages, trolleys or gaylords[9]. The most effective method to introduce these items in the sorting process is to dump the contents of the containers onto bulk conveyors.’ [Sie21, p. 7]. Such a bulk conveyor is depicted in Figure 10.

Figure 10. What looks like garbage are actually polybags after bulk unloading from the transportation containers onto a bulk conveyor and prior to singulation and sortation [own illustration]

At first glance, automated unloading looks like careless handling of the shipments with a high possibility of damage to the contents. But that is actually not the case. The handling of piece good in bulk mode has already been studied in detail. Fritz et al. [FWJ13], for example, published a feasibility study identifying and comparing suitable simulation tools for the modeling of cardboard parcels in bulk mode as well as of conveyor technology such as belt or roller conveyors in order to influence the movement and shape of the bulk. The study showed that both Multibody Simulations (MBS) as well as the Discrete Element Method (DEM) can be used to analyze the trajectories of the items and the forces acting on them to avoid damage while ensuring successfully disintegrating the pile of the parcels in bulk mode.

Further research by Katterfeld et al. has also been conducted considering the so-called ‘Box-in-Box’ problem. A new simulation method (multilevel DEM simulation) for the calculation of freely moving multibody systems was developed, which enables the consideration of external and internal contact forces simultaneously (see Figure 11). The simulation method allows the prediction of the load acting on items inside parcels depending on the forces due to parcel (bulk) handling. The result of the research project[10] demonstrated that this simulation method is suitable for evaluating and comparing technologies for handling parcels in bulk mode with respect to mass flow and impact loads acting on the parcels. [cp. KP21]

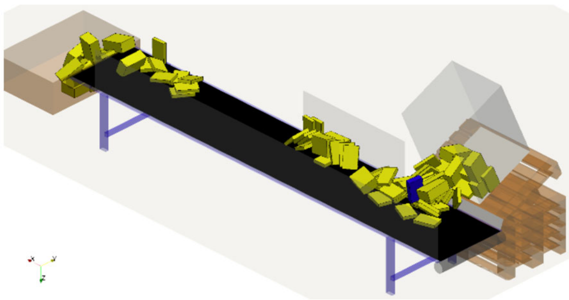

Figure 11. DEM simulation of a bulk feed test of cardboard boxes [PK17, p. 10]

In terms of sorting shipments, however, polybags have not been exhaustively considered in scientific research to date. While being unloaded in bulk mode polybags may change their shape due to their limp or flexible nature as well as content like fabrics. Also, the center of gravity varies as the content slips inside the bag. It still holds true that emptying in bulk mode under normal circumstances[11] does not damage the content of a shipment, but still occurs if the item is fragile and/or the drop height during the dumping process becomes too high. Another issue are polybags that have magnetic content. These shipments get caught on metallic objects of the machine, such as guide fences or light barriers, and in the worst-case cause clogging.

[9] ‘Gaylords’ is a trade name of the former Gaylord Container Corporation. Theses ‘Gaylord boxes’ are large, usually pallet-sized, boxes made from material such as corrugated triplewall board or wood [Sor08, p. 27]. There are also similar types of pallet-sized bulk boxes such as ‘octabins’ (octagonal corrugated box).

[10] Research project: ‘SIMPPL – Simulation of the motion behaviour of filled parcels and load carriers in bulk mode’, Deutsche Forschungsgemeinschaft (DFG) – Project number 281353435

[11] The term ‘normal circumstances’ is fuzzy as it is defined in the respective transport guidelines depending on the CEP service provider. Rule of thumb according to the Austrian Post [Aus20, p. 2]: The packaging of the shipment is sufficient if the contents can withstand a stacking pressure of around 80 kg and remain undamaged after free falling from 80 cm onto a hard surface.

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2. Preparation

The functional area of preparation combines the functions of merging, separating and aligning. The spatially distributed (truck) sources may need to be merged into a single conveyor stream. For automatic identification and discharge from the sorter, the consignments must not lie next to each other and must be at a minimum distance from each other. For stable conveying and orientation, the shipments are also initially aligned longitudinally in the conveying direction. Likewise, the consignments must arrive at the sorter in a defined orientation to enable optimum use of the sorter. [JH12, p. 28]

Based on the concept of handling parcels in bulk mode, further research has also been done by Fritz [Fri16] to analyze the subsequent singulation process in order to develop different kinds of working principles to singulate a large quantity of items. Therefore, more than 70 patents on singulation techniques were analyzed to identify the underlying physical mechanisms. Also the DEM simulation method was identified to be suitable to predict the motion behavior of many items in the singulation process. [cp. Fri16]

Figure 12. Workstation for manual insertion of mixed mail into the actual sortation process [own illustration]

In practice, the process of separation and alignment is still manual or only partially automatic, although fully automated singulation systems that are specifically dedicated to process mixed mail do exist (e.g., Siemens Visicon [cp. Sie21, p. 7]). Observations of manual operation made at a CEP service provider show that the way employees work at the infeed points has a decisive influence on sorting (see Figure 12). The way in which polybags are placed on the infeed conveyors often had a major impact on the exact positioning on the sorter itself, especially if the shipment is very lightweight. If the shape and center of gravity of the polybags are correctly considered during placement, a reduction and even prevention of possible lift-off, rolling and rollover can be observed. Possible reasons include that the inertial forces do no longer have a large impact and/or that the air cannot easily start flowing underneath the shipment during acceleration. It was also observed that experienced staff is well aware of these circumstances and hardly any problems occurred even with critical material.

3. Identification

After the shipments have been separated and aligned, the labels (recipient, address, etc.) are automatically identified and the consignments are assigned to the appropriate sorter end point. Optical Character Recognition (OCR) technology is usually used for this purpose. Due to inadequate sorter feeding, the potential loss of labels (see Figure 13) or simply due to the unshapen nature of polybags, the technology used is not able to perform a robust identification all the time.

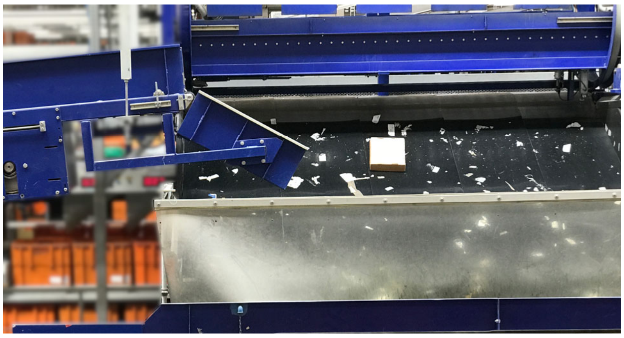

Figure 13. Loss of labels on a chute [own illustration]

An investigation in a sorting hub of a CEP service provider revealed a significant difference in positive OCR-readings. Figure 14 shows the corresponding numbers taken from six day-shifts, where the sorting system (see Table 1 for technical details) was set to only sort mixed mail.

Table 1. Specifications of investigated cross-belt sorter

Properties	Values
Velocity	2 m/s
Number of carriers	250
Length	137.5 m
Max. theoretical throughput	17,410 #/h
Infeed/discharge areas	2/2

As can be seen, only 7.36 % of polybags could be recognized automatically by a single-shot OCR. A further 59.71 % of the shipments could be positively recognized by the employees by means of videocoding. This figure is of particular significance, as it means that it was in principle possible to read the label. The reasons for non-recognition by OCR technology were therefore not due to inadequate insertion, separation or loss of the label. Rather, the OCR technique could not handle the physical characteristics of the polybags, such as being oddly shaped or having a shiny surface. Only 7.37 % of all OCR requests could definitely not be identified by any means.

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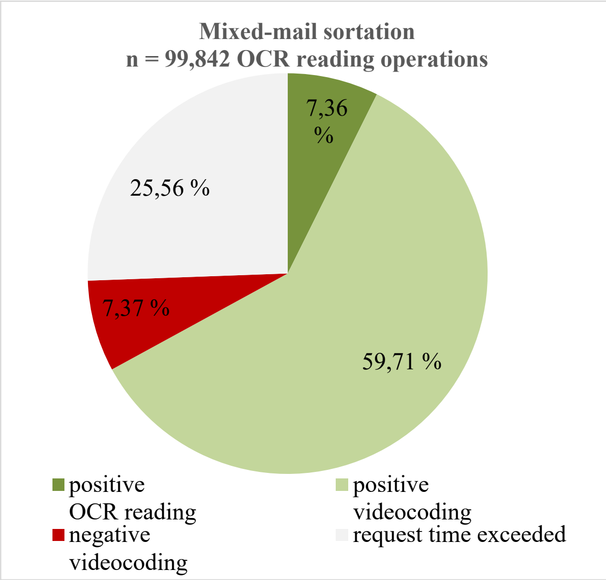

Figure 14. Results from an investigation on OCR and videocoding reading rates [own illustration]

4. Sorting and 5. Discharge

The physical characteristics and in particular the dynamic behavior of polybags also affects the sorting process. The IPC study [Int19, p. 13] provides a weight distribution of cross-border e-commerce purchases based on 33,594 completed responses from a quantitative survey among frequent cross-border online shoppers. As can be seen in Figure 15, the most common weight category over the last five years was 200-500 g.

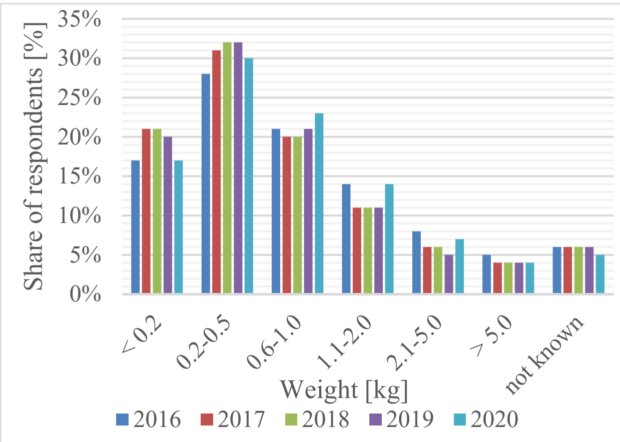

Figure 15. Weight distributions of cross-border e-commerce purchases according to surveys by the International Post Corporation [cp. Int20, p. 14]

In order to gain an even more detailed insight into the predominant weight classes in the sorting of small consignments, the aforesaid investigation in a sorting center of a CEP service provider was also used to record and evaluate the masses of individual items. The data revealed that polybags tend to be very lightweight, as can be seen in Figure 16. In a sample of 14,086 items, more than half of all items (51.99 %) had a weight of 60 g or less. A high proportion of polybags (22.05 %) even weighed less than 20 g.

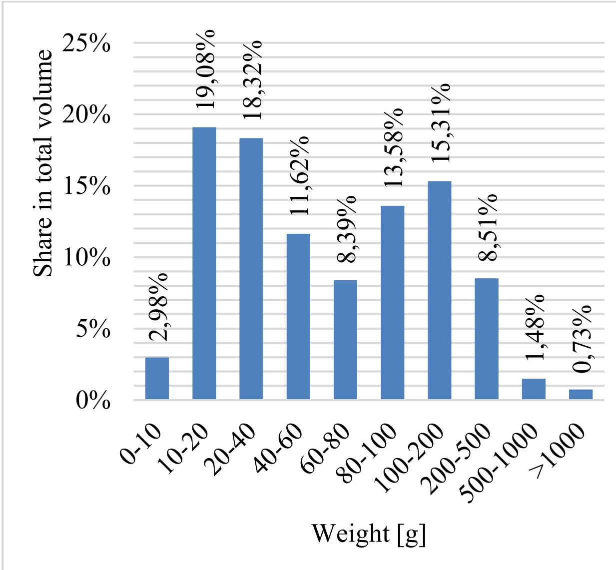

Figure 16: Weight distribution of a sample of 14,086 mixed-mail items that were examined [own illustration]

Processing such lightweight shipments with loop sorters lead to infeed problems and/or slippage of the polybags relative to the load-bearing elements especially in curves, as lift and/or centrifugal forces start to play a major role. As can be seen in Figure 17 this predominantly leads to misplaced shipment (also called ‘intercells’) that can no longer be discharged correctly (4 % of the sample). Subsequently the carriers involved get deactivated, which means that they cannot be used until the misplaced shipment is manually removed. Carrier deactivation inevitably leads to a decrease in throughput. Another but even worse case is that a shipment not only slips but also falls off the sorter and thus leaves the process at all (also called ‘fly-outs’).

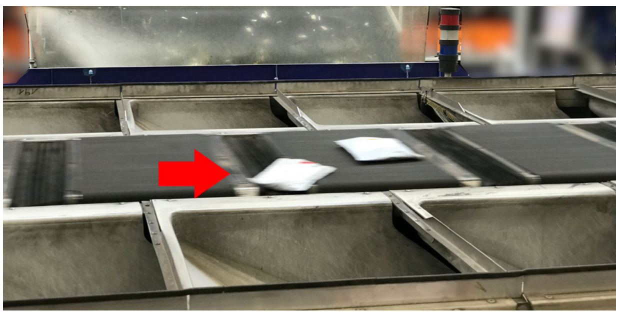

Figure 17. Typical operational issues in the automated processing of polybags: infeed problems on cross-belt sorter due to low weight [own illustration]

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Problems with polybags also occur with line sorters (see Figure 18), where the sortation is often done by flow splitters or castor sorters splitting the continuous flow to several conveyors or into end stations to the side of the equipment.

Figure 18. Example of a flow splitter for mixed mail: Siemens VarioRoute [© Siemens Logistics]

The throughput of such a flow splitting device is determined by the minimum gap between two shipments, which is needed for the rewinding of the rolls into the roller's idle positions. At a roller speed of 1.6 m/s and a time span of approximately 200 ms for rewinding to the idle position, the minimum distance between the mixed-mail items corresponds to 0.32 m. In the worst case, two polybags converge each other such that they can no longer be discharged separately, resulting in incorrect sorting. Since the customer specifies the maximum rate of missorted items, a larger gap must initially be provided, which reduces throughput.

From a scientific point of view, there is a significant research gap in terms of data and knowledge about proper automated processing of polybag shipments. Figure 19 shows an Ishikawa-diagram that lists the described problems and effects according to their occurrence within the five functional areas of the sortation process. Therefore, the purpose of this paper is to characterize the fundamental physical properties of polybags as they can be found in today's shipments. Furthermore, an in-depth analysis of the effect and its root causes with a special focus on the limpness/rigidity and the static and dynamic coefficients of friction (COF) of polybags in comparison to cardboard and kraft paper is presented. The knowledge gained shall serve as a basis for future methods and tools to better consider the specifics of these shipments in the construction and design of automated material handling equipment.

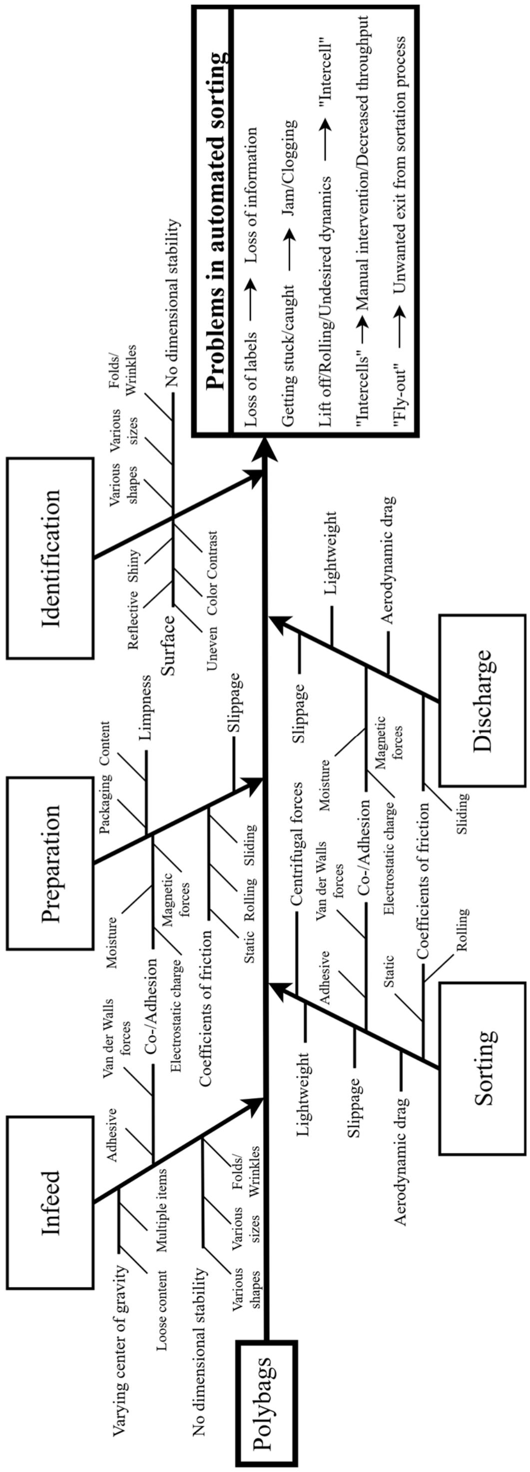

Figure 19. Ishikawa-diagram showing the causes and effects related to problems in automated handling and sortation of polybags [own illustration]

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3 Classification of Polybags

When taking another look at Figure 10 again, it becomes obvious that polybags have very different appearances and therefore have a wide range of possible material properties such as size, weight, dimensional stability, surface condition, and damage sensitivity. These properties are important parameters when selecting the right sorting technology as they have a major impact on the sorting process [VDI17, p. 21]. A simple but systematic description of polybags in order to distinct them from other types of shipments is to classify them according to the proposed property categories of typical conveyed goods that can be found in [VDI17]:

- geometrical shape (cubic, cylindrical, convex, concave, spherical, etc.),
- dimensions (minimum, mean, maximum),
- weight (minimum, mean, maximum),
- center of gravity (invariable/variable position),
- material properties of packaging or conveyed good such as: (see also chapter 3.2)
  - fragility,
  - friction behavior,
  - form stability (rigid, limp/flexible),
  - electrostatic property (e.g., charging),
  - humidity absorption (e.g., polyamide),
  - etc.

This classification was used in an investigation for Siemens Logistics GmbH that analyzed two IPC pallet boxes of another Designated Postal Operator (DPO)[12], which were filled with original shipments that were in transit between senders and recipients (also called live-mail). Primarily, the gathered data was used to investigate the machine capability of shipments on conveyors at different speed levels. In addition, the data was also used for the classification based on the criteria mentioned above. A selection was made from the live-mail, such that the entirety of small mail items is represented in the best possible way. Since the two IPC pallet boxes examined contain only a relatively small quantity of items compared to the entire volume sent, the findings unfortunately cannot be used to describe the entire spectrum of small consignments. The live-mail rather serves as an example to define the objects to be further examined. [cp. Sau19, p. 5]

3.1.1 Geometrical Shape

The basic problem regarding the shape of polybags can be described with the following definition by [CLG+18]. It is based on a comparison of polybags to conventional cardboard boxes with fixed sizes in all three dimensions. 'As to the polybag, whose sizes are only given the length and the width, the space inside it can be variable. Initially, the space is a two dimensional rectangle when no items are loaded. Once an item is loaded into the polybag, the space becomes three dimensional: the height depends on the item; the length and the width are shorten (sic!) accordingly.' [CLG+18, p. 70].

This statement highlights the most significant difference between cardboard boxes and (poly-)bagged goods: dimensional and positional stability. In the case of cardboard boxes, the dimensions do not change on contact with the conveying or sorting machinery. If a change in shape nevertheless occurs (e.g., compression), this is equivalent to damaging the consignment. For polybags a further distinction has to be done, as it strongly depends on what kind of good is packed inside the polybag. For rigid goods a change in shape without damage to the good is possible as long as the change of size only affects the wrapping material. Flexible goods are rarely or never prone to damage although the polybag might change the shape several times as they are generally soft and deformable, which is why they are not considered dimensionally stable. Likewise, deformation does not necessarily result in damage to the consignment. This can be seen in Figure 20, where a change in shape of a polybag with a garment as content is depicted. The pictures were taken before and after a free fall from a height of 80 cm, which is supposed to represent a tough but legitimate work step in the sorting process [cp. Aus20, p. 2].

Figure 20. Change in the shape of a polybag before and after a free fall from a height of 80 cm [own illustration]

Table 2 shows examples of shipments taken from live-mail and categorically classifies them based on various shapes (e.g., cubic, convex, concave, etc.). In the context of goods sorting, positional stability means that the consignments do not leave the position they have reached after fed-in until they are discharged. Positional instability can, for example, lead to rolling of the goods, which is why the freedom of movement of the consignments must be restricted if dynamic forces can cause the goods to move. [cp. VDI17, p. 21]

[12] Name may not be published.

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Table 2. Various shapes found during the examination of the live-mail [Sau19, p. 9]

Shape	Examples		
cubic			
flat			
cylindrical			
convex			
others			

3.1.2 DIMENSIONS AND WEIGHT

When examining the live-mail, the items were first divided into related clusters based on their appearance. Within each cluster, those consignments were selected which represented the lightest and heaviest as well as the smallest and largest items in each dimension. Besides a brief description of the appearance of each cluster, the minimum and maximum of all properties (dimensions, weight) of each selected item were noted in a table together with the contents as claimed on the customs label. The results of each property were compared individually with the minimum requirements of the logistics service provider.

Table 3. Absolute minima of each property for selected items taken from live-mail [cp. Sau19, pp. A-6, A-7]

	Length [mm]	Width [mm]	Height [mm]	Weight [g]
CEP spec.	100	90	5	50
min.	***95***	***35***	***4***	***4***

As can be seen in Table 3, some consignments were below the minimum required mail specifications. Low-value consignments that fall below the specifications listed are very likely to not being processed by current sorting equipment and must therefore be fed to a manual sorting process. In addition to the examination of live-mail, data from the tenders and specifications of three different CEP service providers willing to acquire new sorting technologies were used, since they describe, among other things, the shipments dimensions and weight that a machine must be capable of processing. The data relies on more than 60 million shipments that were analyzed for this purpose by the providers themselves. Hence, this data is used for further cross-checking and fine-tuning the range of each property. Table 4 shows an overview containing the results regarding dimensions and weight on the one hand and the characteristics of the packaging materials and various shapes of polybags on the other hand. [cp. Sau19, p. A-2]

Table 4. Overview of the range of properties of small consignments considering samples from live-mail as well as data from CEP service providers [cp. Sau19, p. 11]

<table>
<tr><th rowspan="2">Properties</th><th colspan="5">Characteristics</th></tr>
<tr><th colspan="2">Minimum</th><th colspan="2">Maximum</th><th>Average</th></tr>
<tr><td>Length [mm]</td><td colspan="2">60</td><td colspan="2">420</td><td>240</td></tr>
<tr><td>Width [mm]</td><td colspan="2">60</td><td colspan="2">420</td><td>180</td></tr>
<tr><td>Height [mm]</td><td colspan="2">5</td><td colspan="2">200</td><td>40</td></tr>
<tr><td>Weight [g]</td><td colspan="2">20</td><td colspan="2">2000</td><td>300</td></tr>
<tr><td rowspan="4">Packaging Material</td><td colspan="3">Plastic foil</td><td>Paper</td><td rowspan="4">Card-board</td></tr>
<tr><td>matte</td><td>thin</td><td>add. protection</td><td>thin</td></tr>
<tr><td rowspan="2">shiny</td><td rowspan="2">thick</td><td>air-cushion</td><td rowspan="2">thick</td></tr>
<tr><td>polystyrene</td></tr>
<tr><td rowspan="4">Shape</td><td rowspan="4">cubic</td><td rowspan="4">flat</td><td colspan="3">cylindrical</td></tr>
<tr><td colspan="3">convex, concave</td></tr>
<tr><td colspan="3">spherical, conical</td></tr>
<tr><td colspan="3">undefinable</td></tr>
</table>

3.1.3 MATERIAL

Polybags can be made from a wide variety of plastics. Which materials are predominant in the CEP industry can only be vaguely determined, as this would require a large sample from live-mail, as well as complex and expensive tests for material characterization. Since China is one of the main sources of polybag shipments, it was decided to take a closer look at the Chinese packaging industry in order to obtain information on the materials offered. In a first analysis the so-called web scraping technique was used to gather a dataset from a Chinese website [Foc21] that lists suppliers of polybags. The initial search terms 'polybag' and 'poly mailer' where used to filter the desired product category. A script automatically checked for specific information on the website, parsed the appropriate text found and saved it to a CSV-file, as can be seen in Figure 21.

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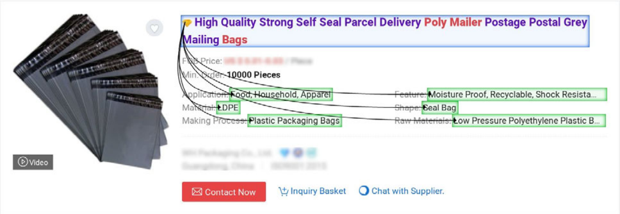

Figure 21. Example of a product entry and information parsed from [Foc21] using the web scraping technique

This data set was used for a quick analysis to find out which materials are mainly used in the production of polybags. The following materials are common:

- Polyethylene (PE) including:
  - Low-density polyethylene (LDPE)
  - Linear low-density polyethylene (LLDPE)
  - High-density polyethylene (HDPE)
- Polypropylene (PP) including:
  - Biaxial oriented polypropylene (BOPP)
- Polyethylene terephthalate (PET) including
  - Vacuum metallized polyethylene terephthalate (VMPET)
- Bio-degradable (co-)polymers using blends of:
  - Polybutylene adipate terephthalate (PBAT)
  - Polylactic acid, or polylactide (PLA)
  - Cornstarch

Table 5 provides an overview of the characteristic material properties of single-layer PE and PP films, as these are among the most common materials.

Table 5. Point of reference for material properties of PE and PP based polybags [cp. Car95, pp. 466, 471, 472]

Pro-perties	Density [kg/m³]	Tensile strength [MPa]		Max. elongation [%]	
		long	trans	long	trans
(L)LDPE (un-streched)	920-930	18-32	16-25	200-800	600-900
(L)LDPE (biaxial streched)	920	30-35	30-32	200-400	400-800
HDPE	940-950	40-55	25-40	500-800	550-800
PP (un-stretched)	900-910	30-60	25-50	800-1200	700-1100
BOPP	910	130	300	180	50

Unfortunately, exact assignment to one material is sometimes not possible at all, because polybags can have multiple foil layers. These multi-material foils can be either produced by blowing into tubular films or as flat films with a (bi-)axial stretching process. Co-extruded foil (also called 'coex foil') can be tailored to provide certain desired material properties like having an inner layer for UV protection, gas or aroma tightness and an outer layer that can be imprinted. Therefore, polybags can be ordered in custom formats, colors and design patterns with a thickness ranging from 0.030 mm to 0.200 mm. Prices vary according to the number of bags ordered, but can get as low as $0.001/piece when ordering large quantities. Figure 22 shows an example of a typical polybag and its features.

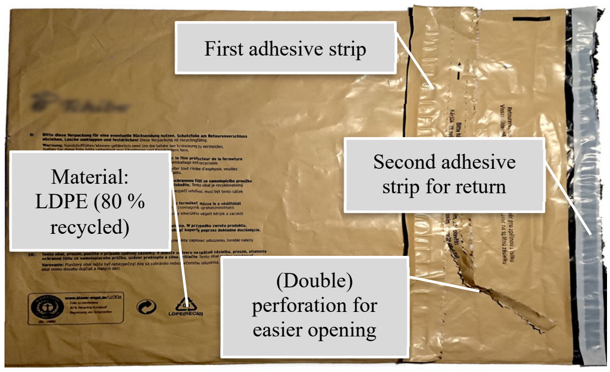

Figure 22. Features of a typical polybag with at least one inner (black) and one outer (brown) foil layer [own illustration]

3.2 Investigation on the physical behavior of small consignments due to material properties

As described in section 3.1.1, general properties of polybags such as shape, geometric dimensions and weight basically depend on the combination of a content with the packaging material. With regard to the sorting process, however, further essential physical properties must be considered, which primarily depend on the properties of the packaging material or the content itself. These include, for example, the determination of the center of gravity, flexural behavior and dimensional stability respectively (combination of packaging and content) or the coefficients of friction (packaging material only).

Since these parameters can only be determined if the packaging and its contents are separated from each other, these measurements cannot be performed on shipments taken from live-mail. This would require unpacking the shipment, which is illegal and therefore not an option. In order to circumvent the problem and still be able to determine material parameters, mail items with either cardboard, kraft paper or polybag as packaging material were collected over a period of two years by the authors. This allowed a total of 41 different samples to be collected providing an initial basis for determining the coefficients of friction and flexural behavior. Table 6 lists all collected items: cardboard is marked in blue, kraft paper is marked in red, polybags are marked in green – air cushion is asterisked.

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Table 6. Collected cardboard, kraft paper and polybag samples (air cushion is asterisked)[13] [own illustration]

No	Sample	No	Sample	No	Sample	No	Sample
1	Cardboard 	11	Cardboard/Foil 	21	Kraft paper 	31	Polybag* 
2	Cardboard 	12	Cardboard 	22	Kraft paper* 	32	Polybag 
3	Cardboard 	13	Kraft paper 	23	Kraft paper* 	33	Polybag 
4	Cardboard 	14	Kraft paper 	24	Kraft paper* 	34	Polybag 
5	Cardboard 	15	Kraft paper 	25	Polybag 	35	Polybag* 
6	Cardboard 	16	Kraft paper 	26	Polybag 	36	Polybag 
7	Cardboard 	17	Kraft paper 	27	Polybag 	37	Polybag 

Table continues on the next page

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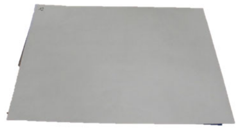
8	Cardboard 	18	Kraft paper 	28	Polybag 	38	Polybag 
9	Cardboard 	19	Kraft paper 	29	Polybag 	39	Polybag* 
10	Cardboard 	20	Kraft paper 	30	Polybag* 	40	Polybag 
Legend						41	Polybag 
	Cardboard		Kraft paper		Polybag		

3.2.1 Characterization of the flexural behavior (rigidity/limpness)

The aim of a categorization with regard to the flexural behavior is, on the one hand, to showcase the different behavior of shipments and, on the other hand, to point out the difficulties of describing properties that are hard to quantify. The flexural behavior of a shipment depends on the properties of the packaging material and the contents (number of items and properties of each individual item). In most cases, the contents are loose in the polybag, which makes it even more difficult to determine the location of the shipment's center of gravity and to find an approach for further describing the flexural behavior. Hence, a generally valid statement is hardly possible due to the infinite number of goods that could be packed into a polybag. For these reasons, two approaches to the description were taken: the first approach (test scenario 1) focuses only on the rigidity/limpness of the packaging material, while the second approach (test scenario 2) categorizes the flexural behavior of the entire consignment as-is (i.e., packaging plus content). The results were categorized into three different classes in each case, ranging from rigid to semi-rigid to limp.

Test scenario 1: packaging material only

In the first test, the specimens were fixed at one end (unilateral restraint) and the resulting deflection was evaluated. The samples selected were polybags no. 31 and no. 32 from the collection shown in Table 6. An additional sample from cardboard served as reference. To ensure comparability between the different specimens, all bags had the same size when unloaded, as can also be seen in Figure 23.

Test scenario 2: entire consignment

Since the contents have a non-negligible influence on the shape of the consignment and thus on the flexural behavior, the second test was carried out on test specimens consisting of contents and packaging in order to simulate a complete shipment. This time, sample no. 31 and no. 34

[13] The purpose of the collection is to determine the material parameters of genuine consignment materials. However, the collection does not claim to reflect the actual frequency of occurrence of individual materials in the CEP market. These distributions cannot be easily determined due to the dynamics of e-commerce and the multitude of packaging materials. The intended purpose also does not necessarily require knowledge of the distribution.

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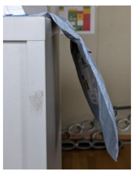
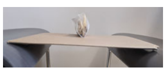
taken from the polybags collection shown in Table 6 were examined, but a mass of 40 g was added to the polybags using woodchips.

Figure 23. Flexural behavior: a) polybags without self-supporting structure, b) with self-supporting structure (air cushion), c) cardboard as reference [own illustration]

It is obvious that the behavior of the shipment varies significantly depending on the combination of packaging and contents. Relatively stiff packaging like cardboard will hold the mass of the contents until the specimen buckles. The same applies conditionally to plastic packaging with air cushioning. Flexural or limp plastic packaging, on the other hand, merely envelopes the contents. The flexural behavior that occurs is primarily determined by the contents themselves. A comparison of the results from test scenario 1 and 2 can be seen in Table 7.

Table 7. Testing the flexural behavior of the entire consignment [own illustration]

		rigid	**semi-rigid**	**limp**
initial state	**undeformed**			
empty	**unilateral restraint**			
filled	**unilateral restraint**			
	bilateral support			

3.2.2 Determination of Coefficients of Friction

Knowledge of the influence of friction between consignments and machine components of all kinds (e.g., chutes, belts) is of upmost importance for the engineering and development of conveyor and sorting technology. But it also becomes more and more important for business customers of logistics service providers. Deutsche Post DHL, for example, provides customers with tips and advice on the correct material, packaging and placement of the label if they use polybags instead of the recommended cardboard packaging. Business customers are instructed, among other things, to use polybags made of LDPE with a dynamic coefficient of friction between 0.15 and 0.2 or polybags made of HDPE with a coefficient of friction between 0.27 and 0.33 in accordance with [DIN04]. [DHL20a, p. 1–2, DHL20b, p. 1]

The countless physical quantities that influence static and dynamic friction between shipments and their environment make it difficult to describe friction with a general valid approach that is applicable to all shipment types and potential friction partners. In literature, [Böc96] is one of the few sources that describe significant influencing factors on friction for consignments made from cardboard, polyethylene, polypropylene, polyamide and paper sliding on an inclined plane (e.g., chute as a sorting station) made from different kinds of steel (blank, coated) or plastics in more detail. According to [Böc96, pp. 4–5, 39], the coefficients of dynamic friction of shipments in general behave as a function of speed and mass (pressure between the bodies respectively) and therefore do not seem to follow Coulomb modelling.

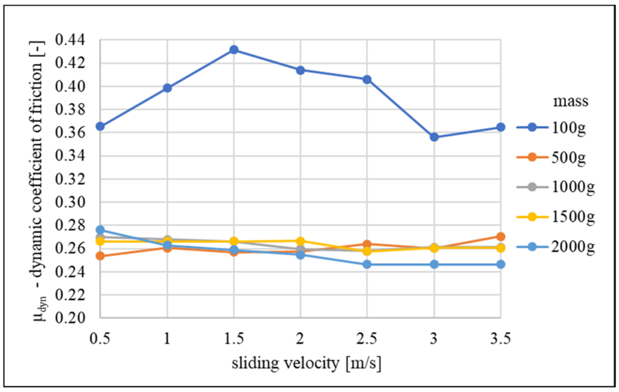


Figure 24. Mean values of dynamic COF of polybags on a blank steel chute according to [Böc96, pp. 146, 147, 155]

Figure 24 shows the relationship between the dynamic coefficient of friction, mass and sliding velocity for polybags. It was observed that the dynamic coefficients of friction can be approximated with linear functions for specimen with higher masses on all surfaces examined [cp. Böc96, p. 71]. The average coefficients of friction of polybags weighing 500 g do slightly increase with higher sliding velocity, whereas they continuously decrease with

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higher sliding velocity with specimen weighing 1000 g, 1500 g or 2000 g. Of particular interest is the finding regarding lightweight polybags since a large quota of polybags weigh less than 500 g, as can be seen in Figure 15 and Figure 16.

Similar tests to determine dynamic coefficients of friction have also been performed by the authors using all specimens shown in Table 6. In contrast to the test setup used by [Böc96] or described in [DIN04], the collected specimen were tested on a slip angle test bench ('Rutschwinkelprüfer RWP') manufactured by the company 'Anton Paar GmbH', which-is also often utilized in the packaging industry to determine static and dynamic frictional resistance of paper, cardboard and plastic foils. [Ant.n.y., p. 1] The measuring principle is as follows: 'Representative test specimens with specified dimensions are taken from the material to be tested and cut. The larger part […] is fixed on an inclinable test plate. The smaller […] part is loaded with a test weight or placed on top of it. Starting from the horizontal position of the test plate, the angle of inclination is increased at a specified speed until the upper part of the specimen begins to slip. The angle reached can be read off the instrument and is defined as the static friction angle. The […] device additionally allows the measurement of the time required for the upper part of the specimen to slide a certain distance. The slipping time serves as an individual benchmark and must be interpreted for each material together with the static friction angle. From this, conclusions about sliding friction behavior can be drawn.' [Ant.n.y., p. 2].

Five test runs with three different friction partners[14] (see Figure 25) were made on the slip angle test bench with each specimen. Each test run determined the slip angle α and the time t of slip along the plate with a length of x. The results of the five tests were averaged and the static (μ_{stat}) and dynamic (μ_{dyn}) coefficients of friction were calculated according to equations 1 and 2.

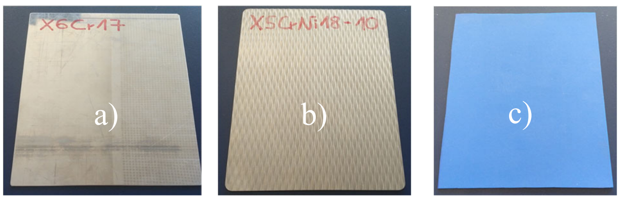

Figure 25. Illustrations of the three friction partners: a) X6Cr17, b) X5CrNi18-10 and c) Rapplon®. The direction of slip is from top to bottom.

$$\mu_{stat} = \tan(\alpha) \tag{1}$$

$$\mu_{dyn} = \frac{g * \sin(\alpha) - \frac{2 * x}{t^2}}{g * \cos(\alpha)} \tag{2}$$

$$\mu_{dyn} = \frac{g * \sin(\alpha) - \frac{2 * x}{t^2}}{g * \cos(\alpha)} \quad (2)$$

With respect to the following results, it has to be noted that the tests to determine the time of slip could not be performed reproducibly for some specimens despite multiple attempts. The reasons were either that the test specimens started to rotate randomly around the vertical axis, which means that the time of slipping down the test plate is no longer comparable or that the material was too thick, such that the test specimen could not be detected at the end of the inclined plate. These values are not considered in the following evaluation and graphical visualization of the dynamic friction coefficient μ_{dyn}. The exact sample size is shown in the legend of the respective diagrams.

Friction partner 1: X6Cr17 steel-plate

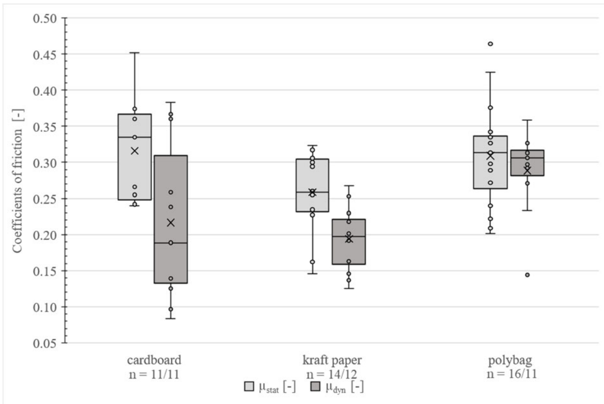

Figure 26. Box plot of the static and dynamic COF of specimens sliding on a X6Cr17 steel-plate

Figure 26 shows a box plot visualizing the results for static and dynamic coefficients of friction for the samples sliding on a X6Cr17 steel-plate. It was observed that in average cardboard has the highest static COF ($\mu_{stat} = 0.316$ with a standard deviation of $s = 0.072$), followed by polybags ($\mu_{stat} = 0.309$ with $s = 0.073$) and kraft paper with the lowest value ($\mu_{stat} = 0.259$ with $s = 0.055$). It also can be seen, that in average polybags have the highest dynamic COF ($\mu_{dyn} = 0.289$ with a standard deviation of $s = 0.058$), followed by cardboard ($\mu_{dyn} =$

[14] The materials selected as friction partners correspond to those used for the relevant components in the sorting machinery.

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0.217 with $s = 0.112$) and again kraft paper with the lowest value ($\mu_{dyn} = 0.194$ with $s = 0.045$).

It can also be noted that the measured values for cardboard are significantly more scattered compared to kraft paper and polybags. This is also to be expected due to the planar contact with actually different contact points. Furthermore, the direction of the fibers or the structure of the (corrugated) cardboard can also play a role.

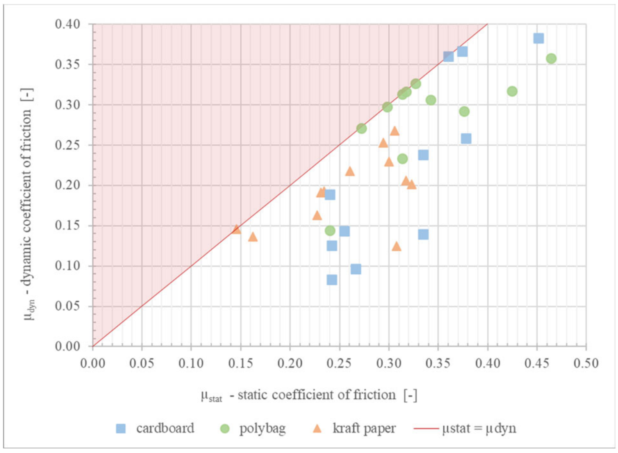

Figure 27. Value pairs of the static (μ_{stat}) and dynamic (μ_{dyn}) COF of specimens sliding on a X6Cr17 steel-plate

Figure 27 shows the relationship between both coefficients of friction. It can be seen that no clear statement can be made when comparing the three material types. At most, a trend can be interpreted that kraft paper tends to have lower static and dynamic coefficients of friction, while cardboard and polybags have higher values. This is also in accordance with [Böc96, p. 74] who also concludes that the dynamic coefficient of friction relative to 0.5 m/s of polybags is always higher than that of paper bags.

Friction partner 2: X5CrNi18-10 steel-plate

Unlike the X6Cr17 steel-plate, the tested X5CrNi18-10 steel-plate is a textured one. Such a surface has a significant influence on the friction coefficients, as can be seen from the results.

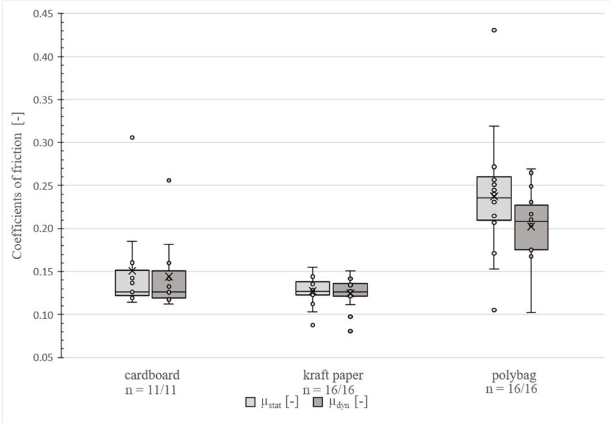

Figure 28: Box plot of the static and dynamic COF of specimens sliding on a X5CrNi18-10 steel-plate

Figure 28 shows a box plot visualizing the static and dynamic coefficients of friction for the samples sliding on the structured X5CrNi18-10 steel-plate. It can be seen immediately that in general both the static and dynamic coefficients of friction are lower and likewise the scatter of the values is comparatively smaller.

It was observed that in average polybags have the highest static COF ($\mu_{stat} = 0.202$ with a standard deviation of $s = 0.046$), followed by cardboard ($\mu_{stat} = 0.144$ with $s = 0.043$) and kraft paper with the lowest average value ($\mu_{stat} = 0.125$ with $s = 0.018$). It also can be seen, that in average polybags have the highest dynamic COF ($\mu_{dyn} = 0.238$ with a standard deviation of $s = 0.073$), followed by cardboard ($\mu_{dyn} = 0.151$ with $s = 0.056$) and again kraft paper with the lowest average value ($\mu_{dyn} = 0.127$ with $s = 0.018$).

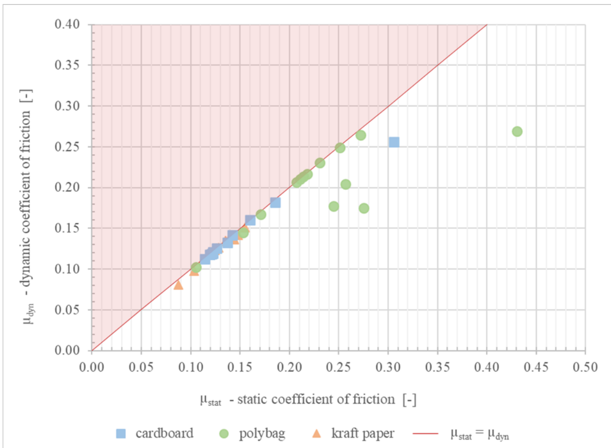

Figure 29: Value pairs of the static (μ_{stat}) and dynamic (μ_{dyn}) COF of specimens sliding on a X5CrNi18-10 steel-plate

It can be concluded that due to the textured surface, an air cushion is formed underneath the samples during sliding, resulting in a kind of lubrication effect and lower coefficients of friction compared to the smooth X6Cr17 steel-plate. Figure 29 again shows the relationship between both coefficients of friction. It can be seen that the values for static and dynamic COF are almost identical, except for a few cardboard and polybag samples, where the static COF is greater than the dynamic one. In addition, the graph also illustrates the fact that polybags in average have the highest coefficients of friction.

Friction partner 3: Rapplon® belt

In addition to the two steel-plates, a conveyor belt, which is often used with sorting machinery, was also included in the measurements. In this particular case, the tested belt has a surface coating of polyurethane with a fine surface texture. Figure 30 shows a box plot visualizing the static and dynamic coefficients of friction for the samples sliding on the selected Rapplon® belt.

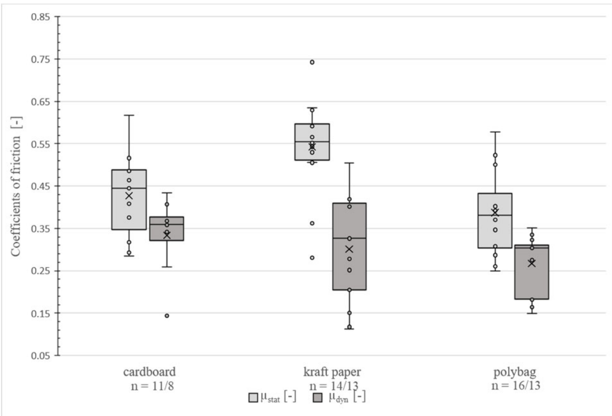

Figure 30: Box plot of the static and dynamic COF of specimens sliding on a Rapplon® belt

As expected, the measured values are generally higher compared to previous measurements. It was observed that in average cardboard has the highest static COF ($\mu_{stat} = 0.334$ with a standard deviation of $s = 0.092$), followed by kraft paper ($\mu_{stat} = 0.301$ with $s = 0.127$) and polybags with the lowest average value ($\mu_{stat} = 0.267$ with $s = 0.071$). It also can be seen, that in average kraft paper has the highest dynamic COF ($\mu_{dyn} = 0.543$ with a standard deviation of $s = 0.113$), followed by cardboard ($\mu_{dyn} = 0.427$ with $s = 0.103$) and polybags with the lowest average value ($\mu_{dyn} = 0.387$ with $s = 0.101$).

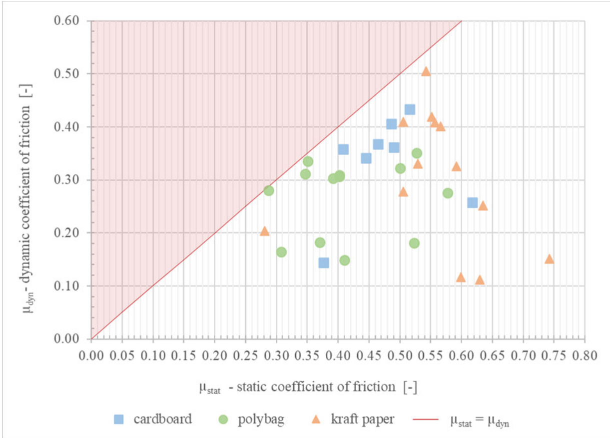

Figure 31: Value pairs of the static (μ_{stat}) and dynamic (μ_{dyn}) COF of all specimens sliding on a Rapplon® belt

Figure 31 shows the relationship between both coefficients of friction. It can be seen that kraft paper tends to have the highest static and dynamic coefficients of friction, followed by cardboard. Surprisingly, polybags tend to have lower coefficients of friction when sliding on a belt.

3.2.3 Influence of the bending behavior on the automated sorting process

In addition to the phenomenological description, the influence of the flexural behavior on the automated sorting process was also investigated on a line sorter test rig consisting of a combination of several flow splitters and belt conveyors, as can be seen in Figure 32. At the test rig, the behavior of small consignments was investigated by measuring the transit times at three modules, since in practice it was observed that certain consignments passing through such a flow splitter exhibit a varying degree of delay. In order to quantify the delay, 401 mixed-mail items with a weight between 6 - 2045 g and a max. edge length between 100 - 465 mm were evaluated on the test rig. The transit times were determined using photoelectric sensors (light barriers) connected to a LabJack measuring device. The value of each item was compared to the transit time of a reference package such that the relative transit time could be determined. In the following, the difference is referred to as transit time delay.

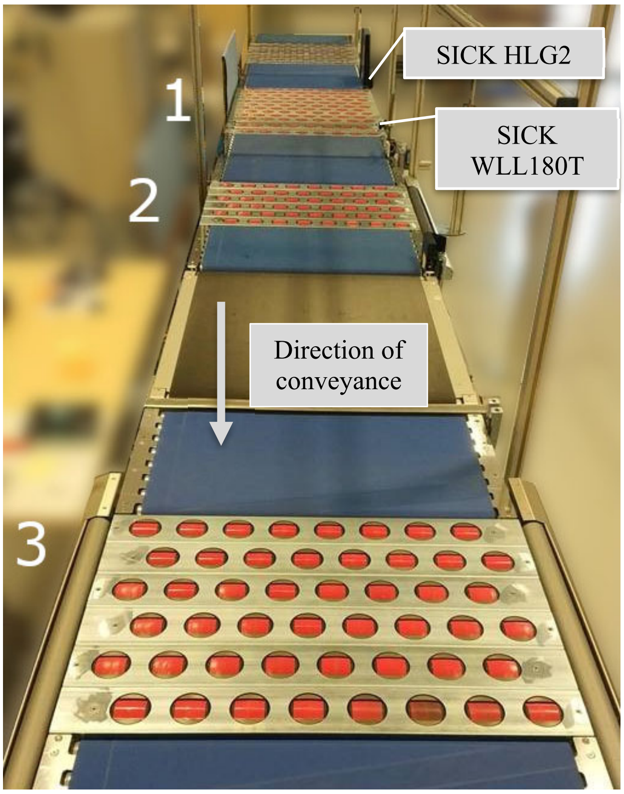

Figure 32. Test rig to evaluate the transit time delay of mixed-mail items being processed by line sorters [© Siemens Logistics]

Figure 33 depicts the relative transit time delays of mixed-mail items plotted against the sample weights and their max. edge lengths in a 3D scatter plot. In the graph, the measured values are color coded, such that the flexural behavior of the mixed-mail items can be seen easily. While rigid items are plotted in gray scale, all values of flexible items are plotted in color. An assignment of the measured values to the individual flow splitter modules can also be made via the gray tones or the colors themselves. Based on the diagram, it can be seen that flexible items are subject to strong delays and the variance in measured values is significantly higher. Small transit time delays were measured for almost all rigid items (few outliers). There is a tendency for smaller and lighter rigid items to be more susceptible to transit time delays. However, a critical ratio of edge length and weight, which significantly influences the conveying process, cannot be clearly derived due to the high deviations in this conveying test. Nevertheless, the test underlines the unique behavior of polybags, which cannot be described by the static or dynamic friction coefficient alone. Therefore, other influencing factors will be discussed in the next section.

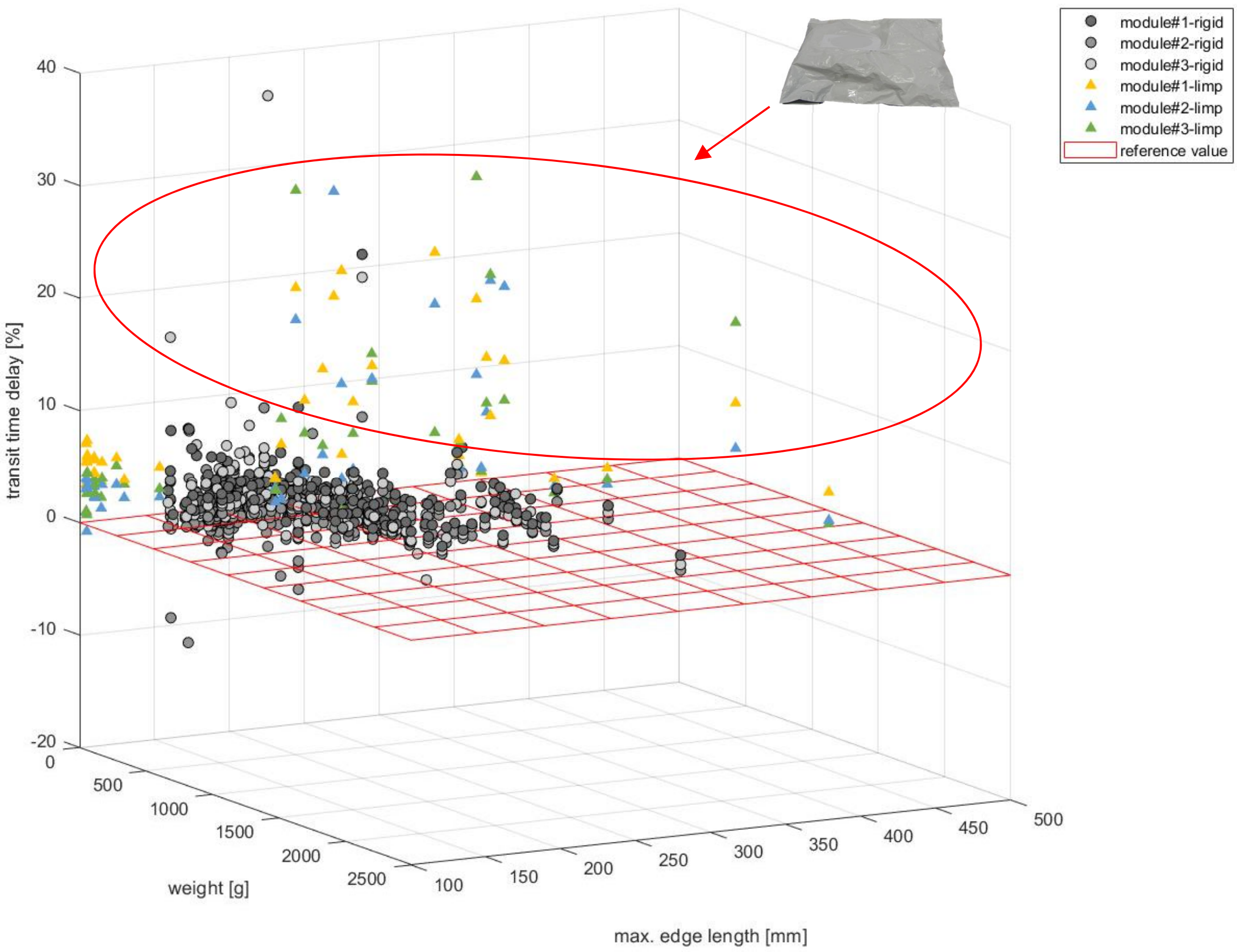

Figure 33. Transit time delay of mixed-mail items plotted against their weights and max. edge lengths [own illustration]

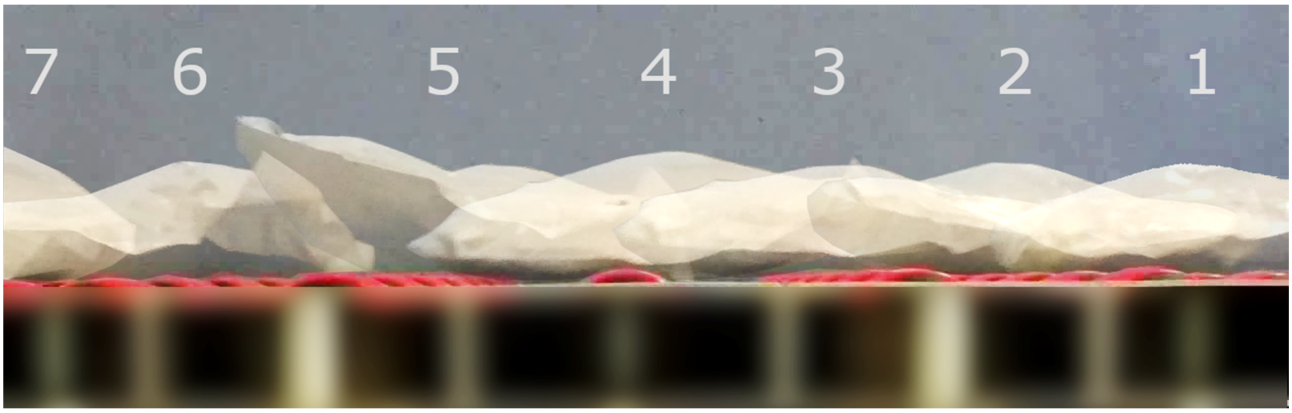

Figure 34. Due to the low material thickness as well as the flexible material property of the polybag, there is defacto no damping between the rigid contents and the passive surface of the sorting machinery. Although the contact is still separated by the polybag material, there are collisions between the rigid contents of the polybag and the sorting machinery, which leads to the temporary lift-off of the shipment. [© Siemens Logistics]

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Subsequently, an attempt was made to find reasons why extreme transit time delays occur with flexible items. For this purpose, the motion behavior of a medium-sized item[15] with a transit time delay of more than 350 ms was analyzed by means of slow-motion video recording. Figure 34 shows the movements of the selected flexible polybag by superimposing individual frames taken from the video recording. As can be seen, temporary lifting of the polybag occurs due to collisions between the rigid contents of the polybag and the sorting machinery.

3.2.4 Other influencing factors

For a comprehensive assessment of the machinability on specific sorting machinery, a more in-depth analysis of the other parameters beside the flexural behavior and coefficients of friction is also recommended, since other influences, such as electrostatic charging, air cushions, elevated temperatures in places and abrasion, usually also play a role [cp. DIN04, p. 4]. The description of such phenomena proves to be very complex, since some of these parameters (such as the area of the contact zone, the geometry itself, the position of the center of gravity, etc.) are not directly accessible by measurements, since they can change on the same object as a result of the sorting process. Nevertheless, an attempt was made to observe further parameters in detail by means of exemplary investigations on individual polybags, which will be described in the following. [Böc96, p. 39] also states that '[…] it is likely that, in addition to the material properties of the friction partners involved, the air flow also has an influence on the friction coefficient […].' According to [Böc96, p. 39] '[…] two effects of the air flow influence have an impact on the coefficient of friction:

- the air flow resistance of the body,
- the lift or downforce of the body, especially the influence of the air flow between the bottom of the body and the sliding surface.'

It is obvious that both effects depend strongly on the shape of the body. As already described in chapter 3.1.1, the diversity of complex geometries of polybags makes it even more difficult to determine these two effects in general for polybags. Therefore, the calculation of the air resistance or lift is not straightforward. Nevertheless, since the majority of polybags are lightweight and/or have a streamlined shape, the aerodynamic phenomena must not be neglected. A first CFD simulation was done exemplarily for a single polybag as a proof-of-concept. Prior to any computational analysis, a 3D-models has to be prepared. There are several approaches to transform real objects into virtual 3D-models like laser scanning or photogrammetry. Photogrammetry was used as a practical and efficient method for the initial modeling of a single polybag.

By using conventional camera equipment in conjunction with open-source programs for the creation and post-processing of 3D-models, very good results were achieved even for more complex geometries. As can be seen in Figure 35, images of a polybag were taken from various perspectives. These were loaded into the open-source photogrammetry software 'Meshroom' to create a rough model. Subsequently the model was imported into the open-source software 'Blender' in order to refine the mesh structure by smoothing the surface and reducing the level of detail as well as to replace the triangle with a quad mesh. In the next step the surface body was imported into 'PTC Creo Parametric', scaled and converted into a solid body in the form of a shell (thickness <1 mm; material properties: LDPE). Finally, a dummy cuboid was added to the model, which on the one hand represents the contents of the polybag and on the other hand can be used to set the 'consignment weight' of the CAD model. [cp. Haf21, p. 39–41]

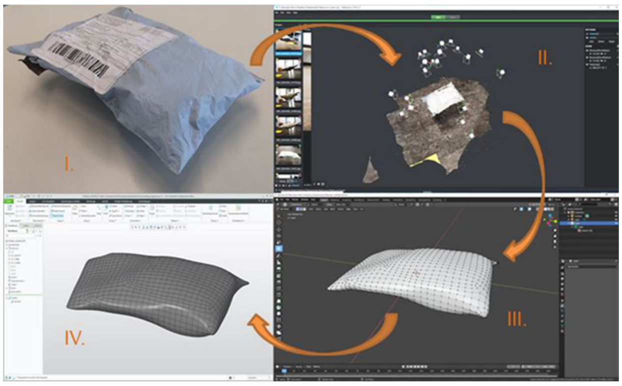

Figure 35. Process steps in the application of photogrammetry to create a 3D-mesh and CAD geometry of a polybag: I) photograph, II) 'Meshroom', III) 'Blender', IV) 'PTC Creo Parametric' [Haf21, p. 41]

In order to evaluate the potential influence of the coefficient of friction due to the air flow, CFD simulations of the polybag were carried out using the software 'Ansys Fluent'. In the first series of tests, the polybag was examined at a constant flow velocity of 2.5 m/s from different directions along the vertical axis, in order to visualize the change of the flow coefficients with varying inflow directions, as a consequence of the logistic process. The first results are very promising. Figure 36 shows '[…] which effects can occur to a polybag. The deflection of the streamlines in 'all' directions also underlines the assumption […] that values for flow coefficients of simple

[15] The selected item was medium-sized both in terms of weight and max. edge length (size: 270x235x46 mm, weight: 756 g).

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2D geometries taken from literature cannot describe the [...] prevailing flow behavior sufficiently well.' [Haf21, p. 46].

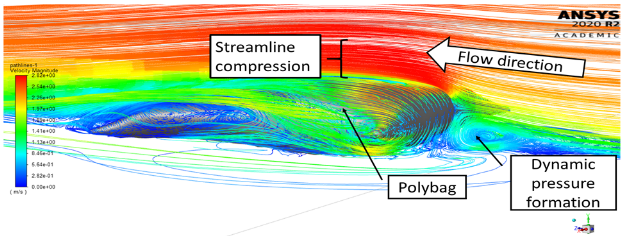

Figure 36. *Result from a CFD simulation: streamlines around a polybag showing the formation of dynamic pressure [Haf21, p. 46]*

4 Summary and Outlook

Based on the impact of e-commerce and the rapidly increasing volume of mixed mail and especially low-value consignments, the basic and manifold problems in the automated sortation of polybags were presented in this paper. Furthermore, the methodical classification based on their physical properties according to [VDI17] was described. In particular, the characteristics of materials used, the geometric shape and value ranges in terms of dimensions and mass were presented. Investigation on the physical behavior due to material properties of polybags like the flexural behavior (rigidity/limpness) or coefficients of friction of polybags were carried out. The results show a more differentiated picture of polybags. The static as well as the dynamic coefficients of friction of polybags and cardboard tend to be higher compared to packaging made from kraft paper. In conjunction with the stated problem descriptions from real sorting processes, it can be concluded that not only the friction has a major influence, but also other physical effects are of particular importance. From a scientific perspective, further in-depth investigations and analyses should be carried out to cover the remaining research gaps. The authors plan to publish selected aspects of the topics, such as the following, in future publications:

Simulation of the dynamic behavior of polybags

In particular, the limp behavior of polybags and the varying tribological contact situations due to the shape leads to difficulties when simulating the dynamic behavior of polybags. First simulation test runs by the authors indicate that the dynamic behavior of polybags can be simulated using Multi-Body-Simulation (MBS) models, but it is subject to further research to verify and validate the simulation results. Figure 37 schematically shows a model of a polybag approximated by a spherical composite.

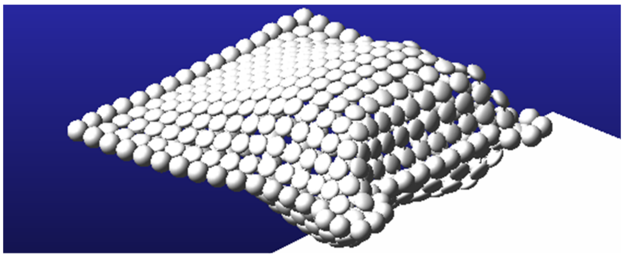

Figure 37. *Spherical model to determine the dynamic behavior in a Multi-Body-Simulation using the software MSC Adams. The model uses 580 spheres to represent a polybag. [own illustration]*

It is also subject to ongoing research to which extend other simulation methods like the Discrete Element Method (DEM) are suitable to describe the behavior of polybags. Suitable strategies to calibrate parameters of DEM contact models for cardboard boxes have already been derived from extensive studies on the mechanical properties, as can be seen in Figure 38 [cp. PK17]. Furthermore, the concept of using so-called 'superquadrics' (single particle per item) instead of the well-established multi-sphere approach to model cardboard boxes proved to have beneficial effects in terms of computational efficiency [cp. PKG+19]. Applying these concepts to polybags needs to be addressed in future works.

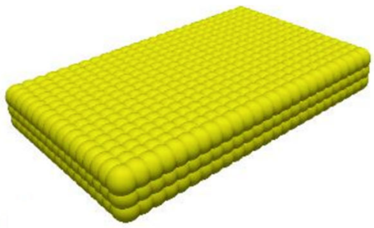

Figure 38. *DEM simulation using the software LIGGGHTS®. The model uses multi-spheres (1275 particles) to represent a cardboard box [PK17, p. 4].*

Simulation of the dynamic behavior of polybags in bulk mode

To simulate the process of unloading polybags in a bulk, both MBS and DEM can be used, as has been shown for cardboard boxes in [FWJ13] and [PK17]. The authors are convinced that these findings can also be applied to polybags as well. In a first step it should at least be possible to transfer the knowledge to polybags with rigid content.

Pattern recognition to sort based on type of consignment

An initial quick and dirty approach also attempted to use machine learning algorithms for mixed-mail sorting. The basic idea behind this approach is that an additional pre-sorting process is introduced, that is done based on the type of consignment (cardboard, kraft paper or polybag) so that a single-sort consignment stream can be feed into the appropriate sorting machine.

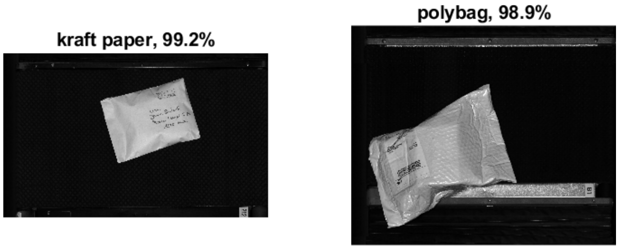

Figure 39. Classification based on a machine learning algorithm applied to images taken from live-mail [own illustration]

To minimize the effort of training a new neural network, the concept of ‘transfer learning’ was used. ‘Transfer learning reuses knowledge from past related tasks to ease the process of learning to perform a new task. The goal of transfer learning is to leverage previous learning and experience to more efficiently learn novel, but related, concepts, compared to what would be possible without this prior experience.’ [cp. YHC13, p. 161–162]. In a first attempt the pre-trained ‘GoogLeNet’ network was retrained in Matlab by replacing the last layers with new layers that were adapted to a new dataset containing 964 pictures captured by a real-life identification system in a sorting hub of a CEP service provider. Although this was just an initial trial an overall prediction accuracy of 85,12 % was already achieved.

Further research

With this completely new topic area of applied logistics research, the authors have shown the potentials and gaps in research as well as first promising results. Therefore, they invite all interested researchers, companies/suppliers as well as logistics service providers to network with each other in order to jointly follow the outlined research paths of this article.

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