Addressing Uncertainties in WEEE Plastic Flows

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1 Introduction

The production of synthetic plastics underwent a fundamental transition during World War II, driven by warfare's unprecedented scale of material intensity, shortage of natural rubber, and the versatility of synthetic polymers [1, 2]. The newly installed infrastructure for synthetic plastics production found purposes after the war by fulfilling the needs of the upcoming consumer society [3].

Since then, the cumulative production of primary plastics between 1950 and 2019 is estimated to be 9.5 billion tonnes [4]. With the durability of plastics against physical and chemical stresses together with a low reuse and recycling rate, plastics have been accumulation in the environment including animal and human bodies [5, 6, 7, 8].

Against further pollution, the EU has introduced numerous action plans and directives that either in- or directly address plastic consumption and waste collection and treatment. First, the Marine Strategy Framework Directive addresses marine pollution and its monitoring [9]. Second, the Zero Pollution Action Plan aims at improving water quality by reducing plastic litter at sea and microplastics released into the environment [10]. Third, the Single-Use Plastics Directive aims at preventing and reducing the impact of certain plastic products on the environment and on human health [11]. Finally, as part of the Circular Economy Action Plan the EU laid out a Plastics Strategy with the aim to improve the economics of plastics recycling and achieve a plastics recycling rate of 10 Mt per year by 2025 [12, 13].

To support the Circular Economy Action Plan and it's plastic recycling target, detailed knowledge of material cycles regarding, quantities, qualities, and locations of plastics containing commodities are required. This is achieved through material flow analysis (MFA), which models the flows of materials through society and it's technological arrangements. In the past, such analysis has often been done in reaction to debates and bans on certain plastic types, as only then was it possible obtain information to quantify and trace plastic flows [14]. Examples here are the case of polyvinylchloride (PVC) in Sweden [15], global leakage of polychlorinated biphenyls (PCBs) [16], and polybrominated diphenyl ethers (PBDEs) in the US and Canada [17]. Since the plastics pollution problem has attracted more media attention due to the discovery of micro- and nano-plastics and ambitions plastics recycling targets have been set, attempts have been made to model plastics flows on a broader and more detailed level. This has been done by further splitting the plastic fraction of a product group into various plastic types (e.g., PET, PU, ABS, PP, PC, ...), including new sectors and product group (e.g., the textile sector and its product groups), and working on a less aggregated level of product groups (e.g., using `UNU`, `CN`, `PC`, or `CPC` product classifications) [18, 19, 20, 21].

Refining MFA models comes with multiple challenges, especially when including post-consumer waste streams, due to the "invisibility of waste" [22]. One such challenge is the uncertainty of product group attributes, such as service lifespan or material composition (in our case plastic fraction and composition). The service lifespan, which defines the lifespan in which a product is functional, is essential for dynamic MFA that models temporal evolutions of the market. Knowledge of the material composition of a product helps to identify the theoretical volume of certain material that could be extracted from a certain sector or product group. Such product group attributes can be estimated through various methods (e.g., surveys, questionnaires, standards, near-infrared spectroscopy), each coming with it's own advantages, shortcomings and possible biases [23, 24, 25].

State-of-the-art plastic flow models have recently started to account for uncertainties in transfer coefficients, used to described the partitioning of a material through a process [18, 26, 27]. Although the uncertainties in product group attributes have been acknowledged in the past, no plastic flow model has yet incorporated them. This can lead to a distortion of the plastic waste streams, create artificial certainty, and misguide policy interventions. This study advances the current practice of plastic flow modelling through the creation of a database of the commonly used product attributes: product weight, service lifespan, and material composition. Based on this database we are able to provide a theoretical lower and upper bound of the amount of plastics that enter the post-consumer waste stream and could be recycled.

2 Methodology

To assess the uncertainty of product attributes we collected data on product weights, service lifespans, and material composition from reports, scientific articles, and databases which are listed in Tab. 1. These sources use various product classification systems (PCS) to which attributes were linked (see left column of Tab. 1. As this hinders a direct comparison between product attributes in some cases, a PCS had to be chosen to which other PCS can be translated. For such purpose, the UNU key classification systems of products in the electrical and electronic equipment (EEE) sector has several useful characteristics. Firstly, the EEE sector has been studied in more detail than others, as it is generating one of the fastest growing waste streams containing not only plastics but also highly toxic materials [40]. Secondly, UNU key classification systems is constructed such that product groups share comparable average weights, material compositions, end-of-life characteristics and life-time distributions [31]. Finally, several correspondence tables between UNU keys and other PCSs exist.

Product weight	
Publication	PCS
Magalini et al. [28]	UNU v2012
Wang et al. [29]	UNU v2012
Huisman and Habib [30]	UNU v2012
?]	CN v2017
Forti et al. [31]	UNU v2012
Amadei et al. [19]	PC v2020
Souder et al. [21]	PC v2019
Product service lifetimes	
Publication	PCS
Daigo et al. [32]	CPC v20
Huisman [33]	UNU v2012
Huisman and Habib [30]	UNU v2012
Kawecki et al. [26]	Sector
Eriksen et al. [34]	Sector
?]	CN v2017
Forti et al. [31]	UNU v2012
Geyer et al. [35]	Sector
Ciacci et al. [36]	Sector
Drewniok et al. [20]	PC v2016
Bolinius et al. [14]	UNU v2012
Product composition	
Publication	PCS
Geyer et al. [35]	Sector
Accili et al. [37]	UNU v2012
Plastics Europe [38]	Sector
Amadei et al. [19]	PC v2020
Drewniok et al. [20]	PC v2018
Souder et al. [21]	PC v2019
Wäger et al. [39]	Prod. Gr.

Table 1: List of publications from which estimates of product attributes were obtained. The product classification system (PCS) to which attributes were attached in a corresponding publication are shown in the right column.

To translate from official PCSs (e.g., PC , CN , and CPC) to UNU keys, correspondence tables published by Eurostat and the United Nations University were used. The translations aren't however always straight forward and the following points shall be noted. First, although the CN codes have undergone major changes between 2021 and 2022, the most recent correspondence table is between CN version 2019 and UNU keys. Second, direct mapping to UNU keys from PC code lists exist for versions 1993 to 2015 of the latter. For later PC versions the path with the lowest number of translations has to be found, leading either via PC version 2015 or CN version 2019 to the UNU classification. While PC and CN product code lists are updated annually, the HS list is updated approximately every 5 years while the revision of the CPC list happens less regularly with the most recent version published in 2015. As no direct correspondence between any CPC version to UNU keys exist, a translation path via HS version 2007 had to be taken. In cases where unofficial product groups were used, a correspondence based on their descriptions was created with supported by the EEE EU-10 categories. Some works use an averaged attribute for the entire EEE sectors (e.g., [35, 36]) which are compared to the distribution across UNU keys instead of their individual values. Fig. 1 gives a graphical representation how a PCS listed in Tab. 1 was translated to the UNU key classification systems.

Each of the collected data points was filtered depending on whether their geographic scope lies within the European Union (28), to ensure that the product attributes have been sampled a similar economic system. No temporal trend was identified for any of the product attributes. Therefore we kept all data points spanning the period between 1980 and 2022, which is in line with [**?**]. Filtering based on the methods through which product attributes were obtained was not done, as they are an important source of uncertainty studied here. While we changed the data format of all sources from which we collected data, such that they match one database schema, we did not undertake changes in the data itself with one exception. Upon closer inspection of the LiVES dataset published by Daigo et al. [32], we identified false lifespan parameters that were referenced to Cooper [41] and corrected them.

3 Results

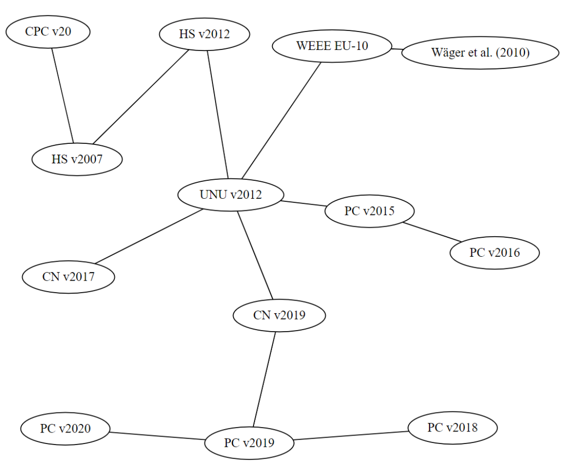

Figure 1: Correspondences graph between all product classification systems used within this study.

In the top row of Fig. 2 we show the estimates of each publication for each product attribute for 20 UNU keys that have the largest put-on-market (POM) quantities (in tons) in the EU (27). We have used the UNU keys as y-axes tick labels, as too much space would be taken by their long name form, which is given in [31]. While some publications provide a single estimate which we indicate by a single vertical line, other have given ranges which we indicate through a shaded region.

On the left column we compare estimates of product weight in kg/pc. We can notice the top 20 UNU keys with the largest POM quantity in tons correspond to products with the largest weight per item estimate (the top three being washing machines, fridges, and household heating and ventilation). In the bottom panel, we show the probability density across all UNU keys weighted by their POM quantity. This distribution shows, that the majority of UNU product groups not shown in the panel above are lighter than 20 kg/pc. When analysing the relation between estimated product weights and the relative difference between the minimum and maximum estimate for a UNU key, an inverse correlation is found. In other words, there is better agreement between different product weight estimates the heavier a product on average is.

In the central column we compare estimates of product service lifespan in years. Service lifespans are given in different forms, such as single averaged estimate, parametric probability functions, or non-parametric probability distributions. For individual UNU keys only the first two were encountered. In case a publication provided a parametric probability function, it's scale parameter was taken as the average service lifespan. Looking at the relation between product weight and service lifespan a weak coupling was found. Products with a service lifespan below 7 years also weigh no more than 25 kg/pc. Therefore, we find a wider range in the probability density shown in the bottom panel, with most products likely to fail between 5 and 20 years. Plotting the averaged weight per UNU key against the relative differences between the minimum and maximum estimate of the service lifespan no trend can be found.

In the right column we compare estimates of plastic fraction contained in product groups. As in the previous case, we can find a weak correlation between a products plastic fraction and weight, in which products with a plastic fraction higher than 0.4 weight less than 25 kg/pc. A clear trend that can be uncovered is the shorter service lifespan of a UNU product the higher its plastic fraction is. Plotting the averaged weight per UNU key against the relative differences between the minimum and maximum estimate of the plastic fraction the following trend emerges. The numerous plastic fraction estimates are more aligned for the heavier products, while their disagreement increases for lighter products.

The dashed lines in the bottom row of Fig. 2 indicate the published estimates for service lifespan and plastic fraction for the entire EEE sector. Concerning the service lifespan, the sector wide estimate given by Geyer et al. [35], Ciacci et al. [36], Eriksen et al. [34], Kawecki et al. [26], and Drewniok et al. [20] are within the uncertainty range across all UNU keys. The only exception is for Bolinius et al. [14], who assumes an average service lifespan of 25 years for products within the EEE sector. Their estimates relied on personal communication from the Swedish Chemical Agency and they acknowledged the likelihood of an overestimation. For plastic fractions the sector wides estimate given by Geyer et al. [35] is likely an underestimate of the true average.

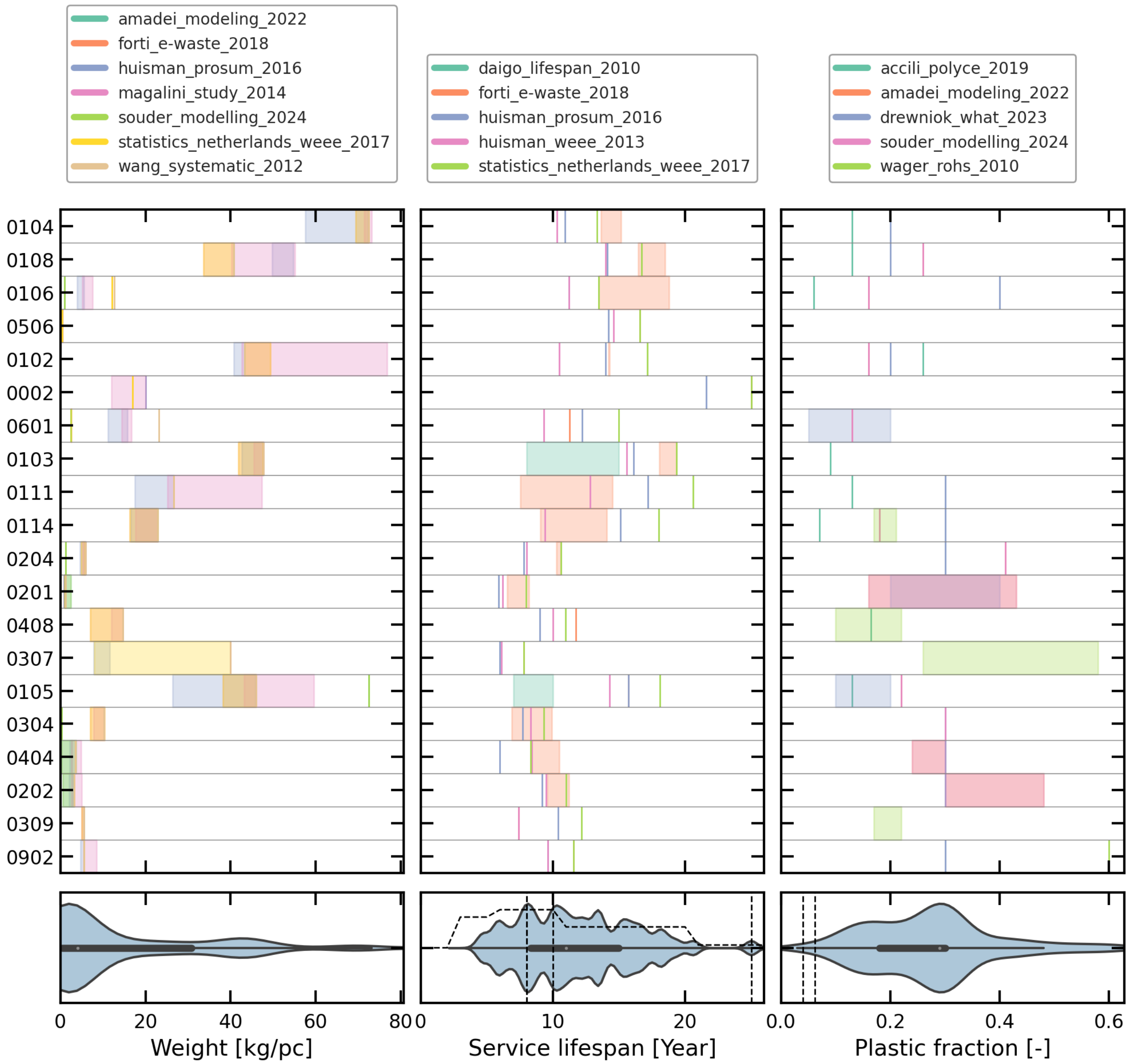

Figure 2: Uncertainties in estimates of product weight (left column), service lifespan (central column), and plastic fraction (right column). The top row shows each product attribute estimate for 20 UNU keys that have the largest put on market mass flow. The bottom row shows the probability density for each product attribute across all UNU keys. Dashed lines indicate published estimates for the entire EEE sector.

In our last step, we applied the identified uncertainties in service lifespan and plastic fraction to the POM quantities per UNU key provided by [42] to forecast the plastic fraction entering the waste stream as product reach their end of life. We show the result for the WEEE EU-10 categories in Fig. 3. The probability distribution of a product attribute was chosen as a top-hat function bound by the minimum and maximum estimate for a given UNU key. This is a more conservative approach when compared to the approach chosen by Kawecki et al. [18] to deal with uncertainties in transfer coefficients. Comparing the amounts of plastic entering the post-consumer waste stream at 2022 of the different WEEE EU-10 product groups we can identify large household appliances (shaded dark green) as the dominant source of plastics, followed by small household appliances (shaded purple), IT and telecommunications equipment (shaded red), and consumer equipment and photovoltaic panels (shaded yellow). Together they are the main waste stream sources, all have a flow mass well above 100 kt at 2022. Of the remaining WEEE EU-10 product groups monitoring and control instruments (shaded grey) leads, followed by electrical and electronic tools (shaded orange), toys, leisure and sports equipment (shaded bright green), and lightning equipment (shaded blue).

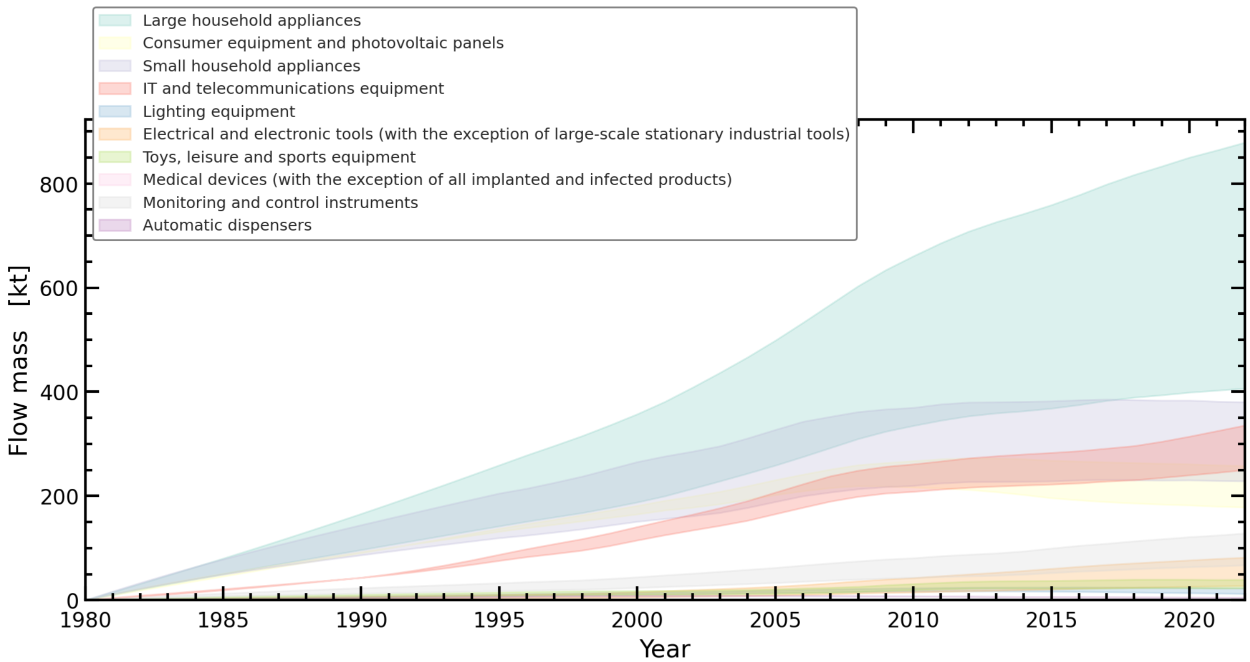

Figure 3: Mass flow time series from 1980 to 2022 for plastics of each WEEEE EU-10 product group entering the post-consumer waste stream. At 2022 large household appliances are the largest source of most plastics, while automatic dispenser contribute the least amount.

When considering the spread of estimates for the year 2022 in Fig. 3, a strong relation between the average flow mass and its uncertainty is found. This means in general, that the larger the plastic mass flow that enters the post-consumer waste stream is, the more difficult it is to confidently state its quantity.

4 Conclusion

Through this work, we are advancing the field of plastics flow modelling by foregrounding and including uncertainties of essential product attributes (such as, weight, service lifespan, and plastic fractions). In this way, we attempt to tackle and reduce the problem of what Strasser [22] named the "invisibility of waste" to a bounded range of possible post-consumer waste flow masses.

Shining a light on these uncertainties is paramount, as they can influence the demand of recycled plastics [43]. It not only impacts the commitment of manufactures to introduce recycled material in new products, but also the willingness of the recycling industry expand their operations to adequately deal with the plastics sourced from the complex EEE waste stream. An estimate made by the Austrian plastics recycling company MGG Polymers on the total amount of WEEE plastics in 2017 lies at 1.4 million tonnes [44]. While their estimate lies within the uncertainty range we modelled for that year, it could be increased by 590 kt or decreased by 240 kt and still be plausible. Introducing these uncertainties around averaged estimates highlight how difficult it can be for, e.g., the recycling industry to forecast their needed capacity or for manufacturing industries to ensure the required amount of recycled feed stock.

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