This paper is in an early draft stage and not for circulation – Thank-you.

WOT? Insights into the flows and fates of e-waste in the UK

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Abstract

In 2019 the EU Waste Electrical and Electronic Equipment (WEEE) Directive documented a sizable increase in e-waste collection targets alongside a wider scope of electronic and electrical products covered by the legislation. These changes have significant impact for the UK, as for the past two years UK waste collected has failed to meet the newly adopted set of targets. Understanding the flows and fates of products on and off the market becomes of paramount importance, especially for producer-led organisations who have the responsibility to achieve the targets and cover the operational costs. Historic e-waste estimations methods often assume that one product on the market will equate to one product in the waste stream. In this article, we report on a project commissioned by one of the largest UK producer-led organisations' – REPIC Ltd, in search of an explanation of the drop-in products on the market and WEEE collected, and the relationship between the two. We argue that we should move away from "one product in and one product out" assumption to include wider parameters that are tailored specifically for the UK, including those linked with the state of the market for electronic and electrical products and of the wider economy, examples include inflation-adjusted GDP per capita, consumer confidence index (CCI), inflation indices (CPI or RPI), number of households, wealth distribution etc. We show how this can be achieved by adapting a state-of the-art e-waste estimation model (Waste Over Time) to the UK context and developing it further to include additional drivers.

Key words: e-waste estimation, WOT, dynamic model, WEEE Regulation, WEEE Directive.

Introduction

The UK Government's 'Our Waste, Our Resources Strategy' (Defra, 2018: 7) supports the ongoing ambitions to reduce avoidable waste and utilise resources more effectively by 2050. Alongside the 2017 'Clean Growth Strategy' there are commitments to investment in sustainable business and job creation, promoting a shift towards a 'low carbon economy' (BEIS 2017: 2). With such ambitions the waste sector is once again receiving considerable focus as waste is viewed both as one of the barriers and solutions to achieving 'zero avoidable waste' and a 'low carbon economy'. With government legislators setting recovery and recycling targets to encourage accountability and resource recapture, and ensure there is suitable funding and responsible disposal as a result, getting insights into the flows and fates of discarded resources (waste) is of paramount importance. Electronic and Electrical Equipment (EEE) is often in the spotlight due to the volumes generated and valuable resources contained within, for example 1.6 million tonnes were discarded in the UK in 2016, equating to almost 25 kgs per person (Baldé et al., 2017).

In 2019, the European Union's Waste of Electrical and Electronic Equipment (WEEE) Directive (2012) documented a substantial increase to the waste collection targets for EEE products Placed on the Market (POM). In addition, the scope of products covered by the legislation increased (European Commission, 2017), to include all EEE unless otherwise stated (Defra, 2017; Defra, 2018), which is referred to as Open Scope. Setting realistic and robust targets is fraught with difficulty due to the current consumer economy and multifaceted routes to disposal (e.g. second-hand markets, incorrect disposal in household bins, theft etc), among other factors (Borthakur and Govind, 2017; Dindarian et al., 2012). These changes have significant implications for the UK, as the legislation is transposed into UK WEEE Regulations, as the recently published 2017 Environment Agency data[1] showed a drop both in EEE POM and waste EEE collected relative to 2016 in the UK. A trend that continued in 2018. "The proposed overall UK WEEE collection target for 2019 is 550,577 tonnes – over 57,000 tonnes higher than the total amount of household WEEE collected and reported in 2018". (REPIC 2019: para. 2).

With the Directive being premised on the principle of Extended Producer Responsibility (EPR), this places accountability, collection and funding for the end of life products with manufacturers (producers) and retailers. Therefore, understanding the economic life-cycle and value of products is vital for producer-led organisations. With the reliance on historical data (Van Straalen, 2016), the changes in post-consumer disposal practices (Borthakur and Govind, 2017; Dindarian et al., 2012) provides the opportunity to re-interrogate the flows of EEE and fates of WEEE in order to see how these changes can contribute to target setting and policy delivery (Stowell, Yumashev, et al., 2018).

In this article, we report on a project commissioned by one of the largest UK producer-led organisations' – REPIC Ltd. One of their aims is to better understand WEEE target setting and the fate of used consumer EEE goods. In search of an explanation of the drop-in POM and waste EEE collected, this project's main aim was to investigate the relationship between the two. Building upon previous academic studies enhancing the estimations of e-waste (Wang et al., 2013; Magalini et al., 2016; Van Straalen, 2016) and industry research (WRAP, 2011; 2012; 2016), we sought to understand, this phenomena in further depth.

Our two key findings suggest that, first of all, the amount of WEEE available for collection needs to be determined for legislative targets. Unreported EEE and WEEE flows (in particular unregistered sellers placing EEE onto the UK market for the first time and via second-hand markets), along with changes in EEE product weight, product lifespan and household residence time, are the key factors to take into consideration to design better compliance targets, understand the implications of Open Scope, and help improve the overall WEEE recycling rates.

Second, in order to accurately predict WEEE generated, detailed production, trade, age distributions of the products in the household and in the waste stream, and unit weight data should all be taken into consideration, including trends in all these parameters. In support of Wang et al. (2013), we also argue that there is a need for a new dynamic WEEE model, which has the ability to estimate annual fluctuations in POM and WG in response to wider socio-economic conditions and specific EEE market conditions (e.g. inflation-adjusted GDP per capita, consumer confidence index (CCI), inflation indices (CPI or RPI), number of households, wealth distribution across the population, percentages of households with no or multiple units of a given product, number of businesses owning a given product, etc). We conclude by putting forward a proposal for what this model could look like, building upon current state-of-the-art model (Van Straalen, 2016), and show how e-waste estimates could be improved as a result.

Our contributions are threefold. Theoretically, we extend the UK e-waste estimations literature through the adaption of the current EU-wide state-of-the art model by developing special *protocols* mapping weight flows from one set of aggregate EEE categories to another (see supplementary data, Appendix A). The new protocols improve our understanding of how the aggregate EEE categories adopted in the UK and EU relate to the underlying granular product databases in the trade statistics (Eurostat), which includes the time-evolution of the mapping as old products get disconnected and

[1] Data is available from https://www.gov.uk/government/statistical-data-sets/waste-electrical-and-electronic-equipment-weee-in-the-uk.

new ones enter the market. Second, we provide new insight into the socio-economic parameters that legislators should take into consideration when setting new targets to enhance overall recycling rates. Last, we ground these ideas in a relevant empirical context – that of EEE waste management in the UK – by providing a deeper overview of specific implications of policy translations for producer-led organisations.

The paper is structured according to the five phases of the research project as each fed and informed the other. We begin by introducing the study of e-Waste flows and fates in the UK context, before moving forward to document our gap analysis of the UK EEE and WEEE data, available models and methodologies. Next, we detail the data elicitation phase reaching out to actors operating in the sector to ascertain further insights. An assessment is then undertaken into the publicly available 'state-of-the-art models' for quantifying products put on the market, the waste generated and collected, with the focus on their applicability to the UK context (e.g. Wang et al., 2013; Thiébaud et al., 2017; Kalmykova et al., 2015; Yu et al., 2010; Van Straalen, 2016). Finally, we identify the crucial data gaps and discuss the implications in a broader context before concluding with our prototype of a new dynamic model for assessing the flows and fates e-waste.

The study of e-Waste flows in the UK:

As indicated above, the transposition of the WEEE Directive into UK law came into effect on January 1st, 2019. Unlike the EU, the UK WEEE Regulation outlines 14 categories opposed to 10, which is due to historic separation of cathode ray tubes, coolants and gas discharge lamps from other waste streams. As a result, the UK chose to convert 14 closed categories to 14 Open Scope categories (Defra, 2017; 2018). The Open Scope categories are extending to include all EEE unless explicitly specified otherwise. In addition to the move to Open Scope, the collection targets are increasing from 45% to 65% of EEE POM in the three preceding years, or 85% if based on WEEE Generated (WG) (European Commission, 2017). As mentioned above, these scheduled amendments have specific implications to EEE Producers and Producer led organisations (also known as Compliance Schemes) in relation to compliance costs and ability to meet the new proposed targets. Against the backdrop of the legislative changes, Repic Ltd[2] commissioned the Pentland Centre for Sustainability in Business[3], Lancaster University to independently investigate and report on existing economic post-consumer forecasting models to understand what socio-economic factors that could be included to improve existing models for estimating the generation of WEEE.

The key aims of the study were to:

- identify possible improvements in EEE and WEEE quantification, including near-term forecasting;
- estimate WEEE generated to enable REPIC to plan accordingly;
- scope further work to develop a dynamic flow model for the UK to improve the forecasts of WEEE generated and help determine collection targets;
- provide recommendations for further work to fill a prioritised list of data gap.

Having more robust estimates for Waste Generated (WG) and improving knowledge of unreported flows of WEEE could enable a richer understanding of the amount of WEEE available for increased targeted collection and assist with future policy setting.

[2] "REPIC is the largest WEEE producer compliance scheme in the UK representing WEEE members who account for half of the weight of electrical and electronic products sold in the UK every year" (2019; para 1 - http://www.repic.co.uk/About)
[3] The Pentland Centre for Sustainability in Business is a transdisciplinary research centre at Lancaster University. https://www.lancaster.ac.uk/pentland/.

This nine-month desk based part-time pilot study took place between October 2017 to June 2018, involving:

- 39 reports and 44 academic research papers reviewed
- 7 models and methodologies assessed for applicability to the UK context
- 5 Technical WEEE experts contacted and consulted
- 46 datasets reviewed and analysed
- 70 organisations and individuals surveyed[4]

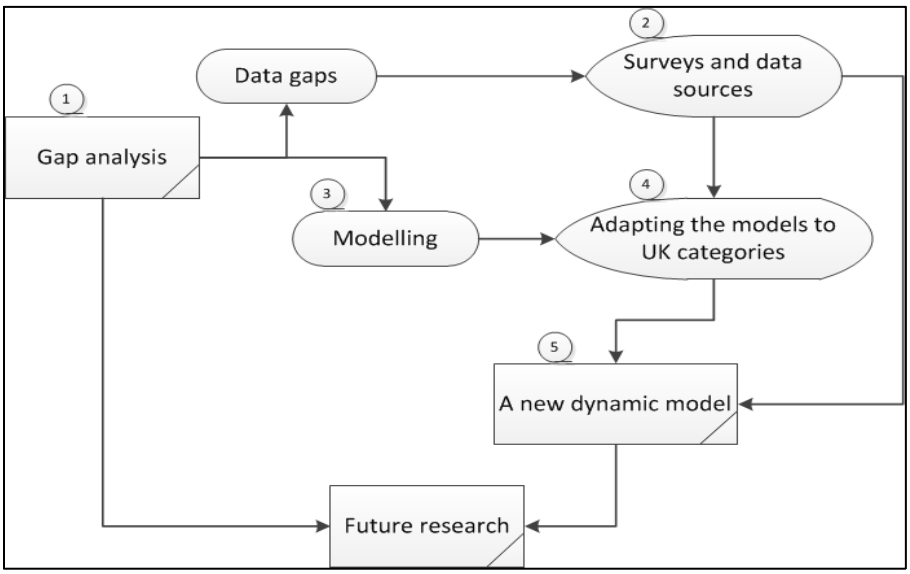
The scope of the project was limited to key policies, product categories and codes as outlined in below. We explored UK EEE POM, WG, WEEE destinations and trends (B2C only) and excluded Second-hand or Used EEE (SHEE/UEEE) and batteries.

Table 1. Key policies, product categories and codes.

Key Policies
EU WEEE Directive (2012/19/EU)
UK WEEE Regulation (2013)
Implementation Regulation (2017/699)
Move to Open Scope (2019)
Product Categories and Codes
6 EU Open Scope Categories
14 UK WEEE Categories
54 United Nations University (UNU) Codes (referred to as “UNU keys”)
500 PRODCOM (PCC) Codes (approx.)
1150 Combined Nomenclature (CN) Codes (approx.)

The research was undertaken in five distinct phases that all fed into each other as outlined in the schematic in Figure 1.

Figure 1. Project phases.



[4] 27% success rate with respondents, 24% members (11 partially responded, 7 full completions) and 21% collectors (9 partially responded with 6 full completions), the return rate is above the expected average for survey respondents (Robson, 2002).

Phase 1 "Gap analysis" examined existing UK EEE and WEEE data, models and methodologies available both publicly and via REPIC Ltd, and identified the key missing information. In the e-waste estimation gap analysis, several models and methodologies were identified[5], showing what (W)EEE estimation tools and forecasting methods are currently available and where possible improvements could be needed. Each data source was scored on the relevance of the discussed methods in the context of forecasting (W)EEE in the UK. See below table 2, if present, contributed to one point towards this score[6].

Table 2. Scoring that presented forecasting models on usability

WEEE forecasting	**EEE forecasting**	**Lifespan and/or residency?**	**Required data available? (e.g. publicly or through REPIC)**	**Suitable for any WEEE category?**	**Total**

Phase 2 "Survey and data elicitation" attempted to obtain data to meet the most common shortfalls identified in Phase 1 - unreported EEE and WEEE flows (e.g. exported used EEE, EEE reused within the country, the amount of WEEE in residual waste, theft and illegal export), product lifespans, residence times, product trends, reliability of publicly available datasets (business to business is largely absent), consumer demographics, technology trends, and socio-economic trends. In parallel, the research team reviewed potential sources of raw data, both available publicly (e.g. Eurostat; company reports) and provided by REPIC (and through the questionnaires). This additional review corroborated the shortfalls identified by the gap analysis.

In an attempt to fill some of the gaps identified, two surveys were designed and sent out to producers (e.g. retailers, manufacturers etc.) (29) and waste collectors, such as local authorities, treatment facilities and waste management companies (41). In the process of producer sampling, the research team targeted companies who manufactured key EEE products in the 14 UK categories, have Business to Consumer sales, predicted growth trends and who have products that are likely to be caught by Open Scope. The survey was carried out on a confidential one-to-one basis, and only the aggregated data was used for this research. The questionnaires include a series of sense-making questions that explore the currently available data and methods. To producers, specific questions were designed to examine their top-three product lines, and the WEEE quantification and predictions of those products. To the waste collectors, specific questions were designed to zoom in on the operational costs and key barriers of recovery and recycling practices. Last but not least, a series of open-ended questions in the survey provided a chance to collect managerial insights and concerns on the challenges and future trends of POM and WEEE. From December 2017 to May 2018, the questionnaires were sent out through emails that linked to the Lancaster University portal of an online survey platform (Qualtrics). Survey responses were consolidated in a spreadsheet, and key features of product-level data were identified that could contribute to influencing (W)EEE flows, for example, fast market growth, decreasing average product weight, short residency time regardless of product lifespan, distribution by unregistered sellers. The qualitative results of the survey, mainly responses to the open-ended questions, were analysed as structured interviews (Robson, 2002) in order to identify key challenges of WEEE management. All data that directly related to the identities of respondents were removed to ensure anonymity.

In parallel with Phase 2, and building upon Phase 1, Phase 3 identified and assessed publicly available 'state-of-the-art models' for quantifying POM, WG and WEEE collected, with the focus on their

[5] A comprehensive of available data models and code lists can be found in the PROSUM 5.5 Report - http://www.prosumproject.eu/sites/default/files/D5%205%20ProSUM_DataModels%26CodeLists_final.pdf
[6] The total score (maximum 5 points) should not be viewed as a quality score of each paper: A paper with a score of 1 might be very good at the one item it covers, while a paper with a score of 5 could have a light touch in each area. This scoring is intended as an indication of the breadth of the paper and relevance to this piece of research.

applicability to the UK context (e.g. Wang et al., 2013; Thiébaud et al., 2017; Kalmykova et al., 2015; Yu et al., 2010; Van Straalen, 2016; Magalini et al., 2016). Seven publicly available models to predict POM and WEEE arising were investigated. These models are based on various methodologies of quantifying POM and WEEE described in the literature. The most useful class of models are based on the input-output-analysis (IOA). A prime example, often reused by other researchers, is the 'sales-stock-lifespan' model developed by (Wang et al., 2013). Further details on a selection of methods appear in Table 3.

Table 3: A selection of available WEEE modelling tools.

Name of the Model	Focus	POM and WG categories	Methodology
Waste Over Time (Statistics Netherlands)	POM, WG	UNU, EU10, EU6 (CN for trade, PCC for production data)	POM & residence times
EU Excel WEEE calculation tool, UK version	POM, WG	UNU, EU10, EU6	POM & residence times
WRAP	WEEE flows	UK14	Disposal, processing and destination splits

The IOA models analysed tend to include the following elements:

- Historic EEE POM data collection from a reliable source, e.g. producers and government data.
- EEE residence time modelling with a Weibull distribution. The Weibull distribution essentially models the failure rate of a product over time. This allows for predictions along the lines of "in the n^{th} year after an EEE product is put on the market, X% of the sold units will become WEEE".
- The prediction of EEE POM across all future years, for which WEEE is to be forecast, based on historic trends.
- The forecasting of WEEE arising through the consideration of historic EEE POM data, forecasts of EEE POM and the residence time distributions.
- Stock levels can also be taken into consideration. Stocks are generally defined as the number of items stored in households and/or businesses, regardless of whether they're still functioning or in use.

- The current generation of the IOA models tend to be driven by the POM data only, while the stock data, if available, serves to calibrate the products residence times. This breaks the immediate link between fluctuations in POM and WEEE associated with stock replacement.

Material Flow Analysis (MFA) is also frequently applied to analyse the fate of WEEE, including its components and materials (Thiébaud et al., 2017; Kalmykova, et al., 2015, Yu et al., 2010). Other methodologies, many of which are discussed in (Magalini et al., 2016; Prosum 5.5, 2019; Prosum 3.1, 2019):

- Time-step method. This does not require lifetime distributions. Instead, it uses stocks, average lifetimes, and sales. The authors (Araujo et al., 2012) claim this is suitable for non-mature markets, or in situations where lifetime distributions are not constant.

- Sales with average lifespan (Wang et al., 2013).

- Carnegie Mellon methodology (Dwivedy and Mittal, 2010).

- Leaching methodology: Determine the total current stock of a product and use its average lifetime to determine the percentage of this stock that becomes WEEE each year (Arauja et al., 2012).

- Stock and lifespan distribution (Huisman et al., 2012).

Eventually, the Waste over Time (WOT) model (Van Straalen, 2016) was identified as the most comprehensive tool currently available in terms of the granularity of the underlying historic data and near-term forecasting capabilities. WOT uses historic data for trade (expressed in CN codes) and manufacturing (expressed in PCC codes) for each EU Member State, available from Eurostat, to reconstruct POM as far back as 1980 for 54 aggregate EEE product categories referred to as UNU codes (ibid.). It then applies product household residence time distributions for each UNU category inferred from available age profile studies and manufacturing lifespan data to translate historic POM into WG. Due to its advanced features, WOT was therefore used as the default model for the analysis. A simplified Excel spreadsheet version of the WOT model was also used for specific tasks (this version supports the Implementing Regulation as a methodology to identity POM and Waste Flows for each EU Member State).[7]

In addition to the assessment of the current models, and to improve understanding of the WOT and Excel models, the research team conducted technical discussions, on skype and via email, with some of the leading experts in modelling EEE and WEEE flows (UNU, Statistics Netherlands, Sofies and WEEE Europe).

Phase 4 then applied the results from a leading model, originally available for 54 UNU codes, to the 14 UK WEEE categories. To adapt the results from the WOT model, which are presented in UNU keys, to the UK categories, a special *protocol* mapping weight flows from one set of categories to the other is required. Developing such a protocol is necessary because multiple UNU keys map onto more than one UK category, making it impossible to simply add together the weight flows for each of the UNU keys in order to get the corresponding flows for the UK categories. The same applies to the UK-EU categories mapping, which will be required in order to report the UK data for POM and WEEE collected in 6 generic EU categories to be reported against from 2019 onwards.

[7] The EU Excel Spreadsheet is publicly available and can be found following this link http://ec.europa.eu/environment/waste/weee/data_en.htm

Mapping aggregate categories such as UNU and UK onto one another requires a higher level of granularity in terms of differentiation between the products. Such granularity is provided by CN product codes. A considerable amount of time and effort was invested into establishing the most complete list of CN products that are in the scope in the UK, both currently and under the Open Scope regulations. Part of this analysis involved updating the existing mapping between CN codes and UK categories, and creating a new mapping for the codes that previously did not have one.

The team also investigated historic changes in the mappings between CN, PCC, UNU and UK categories, and developed time-varying UNU-UK-EU protocols that reflect on these changes and projects the WOT model output onto the UK categories. There are separate UNU-UK-EU mapping protocols for POM and WEEE because the latter consists of EEE products that were being sold throughout the historic period (according to the residence time distributions), and therefore the WEEE mapping in a given year includes the POM mappings for all the previous years.

The POM mapping protocols also provide a methodology for filling the data gaps for POM on the CN level, which involved developing an intermediate PCC-UK protocol.

Finally, building upon all of the above, Phase 5 developed a prototype for a new dynamic model for POM and WG, as called for by Wang et al. (2013), and identified the crucial data gaps. The new model is driven by several socio-economic and market parameters that have not been included in the current generation of the IOA models. The model is able to reconstruct historic POM estimates from WOT with a good degree of accuracy and provides a plausible explanation of how both POM and WEEE generated have been responding to year-on-year fluctuations in the economy.

Results and relevance:

Subsection: UK EEE and WEEE data, models and methodologies

The e-waste estimation gap analysis results highlighted the variety of products that are contained in each of the 14 UK (W)EEE categories (e.g. Yu et al 2010). The residence times and weights of these products can vary substantially, even within their respective categories (e.g. Wang et al., 2013; Bakas et al., 2014; Van Eygen et al., 2016; Wilson et al., 2017). Thus, in order to predict the total amount of WEEE arising, the analysis indicated that it would be better to initially work with more refined product categories, so that typical weights and residence times are more similar within each category (Van Straalen, 2016). Once the WEEE predictions have been made for these more granular categories, these can then be merged to obtain results for the 14 UK categories. To make accurate predictions, it is therefore necessary to have the following information for each product category of interest:

- Historic sales data, as a product count per year. Ideally this sales data would span back to the 1980s, as some of the products sold back then still contribute to WEEE arising today (ibid).

- Average item weight in the category (ibid).

- Product residence time distribution (Wang et al., 2013; Van Straalen, 2016).

Residence time distributions can vary over time. For example, recent trends show that product lifetimes are generally becoming shorter, which may lead to shorter residence times (dependent upon the product). One way to estimate residence time distributions is to ask producers to estimate after how many of the items in a category will have been discarded in years - 25%, 50%, 75% and 90% (TemaNord, 2009). It is not unusual to have an initial spike of WEEE resulting from a new product on the market, e.g. due to teething problems or some customers disliking the product. Therefore, producers should also be asked to estimate the percentage of items discarded in the first year (ibid.).

A common issue for WEEE forecasting methods is that historic sales data can be difficult to obtain. While this doesn't matter much for products with shorter residence times, it is a problem for products with longer residence times. To resolve this, extrapolation/back-casting techniques are sometimes used (e.g. Bakas et al., 2014) to estimate EEE POM data as far back as the 1980s.

EEE POM

To establish EEE POM the WOT model (Van Straalen, 2016) uses sales data. When national production data is available instead, imports and exports need to be taken into account. In that case, the total sales of EEE are usually calculated as follows:

EEE sales = total domestic production + imports – exports

This is known as the Apparent Consumption method (Prosum 3.1, 2019).

Mature and growing markets

Some product categories have reached a certain saturation point, beyond which sales and disposal are strongly correlated. For example, if someone buys a new fridge, they are also more likely to be getting rid of an old fridge. New technology, which has not yet reached a saturation point, often shows an initially accelerating penetration rate. This eventually slows down and then levels out at some approximate saturation point. TVs however may be moved to another room in the building. An example of this can be found in a study to derive the penetration of computers over time in Algeria (Hamouda, et al., 2017).

The key findings from the gap analysis can be summarised as follows:

- The best available (W)EEE forecasting methods use historic sales data, in combination with product lifespan or residence time distributions, in order to forecast WEEE.

- The best available (W)EEE forecasting methods have not previously been tailored for the 14 UK categories.

- One drawback of current methods is that lifespan distributions are fixed based on the year of sale. However, in reality, lifespan distributions are likely to change due to various factors, such as economic influences, consumer preferences and new product developments (or lack thereof). The prototype dynamic model developed during Phase 5 of the project provides a feasible way of rectifying this shortcoming.

Subsection – Unreported flows – survey

In Phase 2, the surveys, was an attempt to capture data that could fill the gaps outlined above and yielded both quantitative and qualitative insights from producer led organisations, retailers and those operating in the reuse or recycling space. The results included individual product line or aggregate category-level estimates for residence times, unregistered sellers, product trends and other factors.

Despite being a relatively small sample size, the producer led organisations who responded to the survey covered a wide range of product lines, ranging from kitchen appliances, dish washers, to Wi-Fi routers, indicating a good coverage of small and large appliances as well as consumer equipment. The data indicated that fast market growth, decreasing average product weight, possibly short product residency time (regardless of lifespan), product distribution by unregistered sellers and possible contribution to WEEE sooner than the designed obsolesce, had the potential to significantly influence (W)EEE flows.

The most significant result was the differences between designed product lifespan and household residence time (64% of the respondents), suggesting that in order to estimate the WEEE arising based on sales data in previous years, it is not sufficient to adopt the technological parameters (such as designed lifespan) from producers. In contrast, it is crucial to:

1) gather household-level data of product residence through the consumer end, and/or
2) predict WEEE arising in relation to a wider socioeconomic context.

37% respondents indicated that unregistered sellers had become a concern for certain products, mainly small appliances and consumer equipment. Unfortunately, neither the survey nor the data discovery have been able to provide any more details about unregistered sellers, but the survey results indicate that they might contribute to 5-10% of market share for given products.

Moreover, across the 14 UK categories, survey respondents have been asked to estimate the past and future market change of (W)EEE. Based on the preliminary results, the surveyed producers and the collectors shared similar insights on the changing patterns of (W)EEE, suggesting that some product categories will have a fast market growth. The volume of WEEE would most likely increase in product unit count, but many products are becoming lighter. The product diversities in all categories are going to increase, which might lead to even more complexity to the planned implementation of Open Scope.

Through the survey, the research team mainly looked into the following aspects of WEEE management insights: data and methodology gaps for EEE and WEEE quantification, managerial challenges, operational costs of WEEE collection and recovery, concerns on future trends, etc.

The results revealed that in the business sector, the data and methods of estimating EEE and WEEE are extremely limited. Respondents commented on the common methodology for estimating WEEE (European Commission, 2017), which is at the basis of the WOT model (Van Straalen, 2016), stating 'nothing is perfect', given that no other proven methods are currently available. However, some limitations were noted, in relation to the estimates being based upon past user behaviour and unforeseen market circumstances. Triggering concerns on how well the common methodology could adapt to rapid or significant changes in product development.

The collectors, on the other hand, indicated that they gathered and monitored data on EEE POM; WEEE collected through producer compliance schemes (e.g. REPIC), WEEE exported, non-obligated WEEE and WEEE collected, reused and recycled outside of producer compliance schemes. With both survey groups reliant on the data consolidation work of producer compliance schemes this highlights the importance of this source.

The producers and collectors mentioned that the following managerial waste management challenges were not taken into account when setting targets for legislation:

- Unreported flows, second-hand markets, discrepancies in product lifespan and household residence times, and component part removal/theft were indicated as factors that could impact the differences between WG and WEEE collected and cause an imbalance in National Target setting for producer compliance.

- Cooling Appliances: the UK market has limited capacity of processing this category. There is only a small number of refrigeration recyclers based in the UK, therefore there are high gate fee charges to dispose of these units.

- Price sensitivity of scrap/iron. If there is any future price disruptiveness in the scrap value, it would be financially difficult for the facilities that operate the dismantling process. In contrast, if spot prices are high, the PCS access to WEEE will reduce.

- Retailers in the market may conduct activities that indirectly restrict the access to WEEE by the PCS. For example, retailers collect old products on home delivery for a fee paid by the consumer, so they have an income stream to offset the cost of collection. Or retailers are building their own recycling plants.

- Small appliances are less viable to reuse, as new goods continue to be put on the market at low cost and with limited durability.

- The producer compliance system does not always meet the full cost of collection, transport and processing, other than for Local Authorities, so there can be a cost attached for other third parties involved in reuse and/or recycling. At the same time the illegal export and extraction of higher value scrap provides a demand for material outside the system.

The collector, recycling and reuse respondents had concerns with the increase in costings attached to fates of EEE. Noticing that their operational costs had increased attributing the causes to increases in labour costs, insurance premiums (due to limited understanding of the hazards associated with process and treating WEEE), and fuel prices. Plus changes in product weights, investment in plant technology, on-going training requirements outlined in legislation (The Waste Management Licensing Regulations 1994), compliance with legislative and industry standards, low gate fees, complementary flows, uncertainty of feedstocks, reduction in the value of metals and plastics and the availability of producer compliance scheme funding or the funds were not covering the costs adequately. Furthermore, indicating the need for wider parameters to be included in future modelling techniques.

Although the survey results suggest that the collectors are concerned about a variety of operational costs during WEEE collection and recovery, not many respondents indicated that they had plans to increase

The Circular Economy Package, innovation and technology trends and uncertainty in markets were other elements explored with the respondents and could impact upon the flows and fates of EEE.

A UK Circular Economy transition the producers and collectors commented on the potential effects:

- No clear policy direction - New business models will evolve but it is unclear how, what will change and when. For example, strategic interventions aimed at improving circularity of UEEE and WEEE through binding reuse targets, improved EPR has the potential to reduce costs and increase income. However, if the business model remains focused on the suppliers retaining ownership of the goods, it may reduce their availability for reuse.

- Increase and expansion in the repair of EEE as is currently done with single domestic appliances. Giving rise to the further availability of component parts that can be used in repairs e.g. TVs.

- Increase and decrease in quality second hand/used EEE sales. Examples were given of an increase for lower income households and decrease in sales due to the purchase of EEE become cheaper making reuse markets financially unviable.

- Increase in product rentals for low-end goods but with purchase remaining favourable for high-end goods.

- The impact of the UK leaving the EU on the Circular Economy. If confidence is low people may spend less money on buying newer models and extend the life of their current equipment.

- The adoption of Circular Economy could potentially create additional costs if legislation forces the business models to change.

Second, we discovered that the major concerns, besides the changing weight/size of (W)EEE, for future trends in innovation and technology are around battery and internet technologies. Despite batteries not being included in the weight of EEE and WEEE, the collectors raised significant concerns. In particular, since an increasing part of the market moves to secondary (rechargeable) from primary (single use), the time that batteries remain on the market is lengthening. The rechargeable batteries normally last the lifetime of the product (typically 5 to 10 years). Such facts bring additional concerns to recovery capacity, disassembling, as well as fire safety issues in WEEE collection and storage. Other concerns regarding future trends include the increasing use of internet-based components in household appliances (e.g., smart kitchen, voice recognition technologies etc.), so that more and more products will have Wi-Fi components, which lead to potential difficulties of dismantling and recovery. Other technologies mentioned included transparent TVs and AI robots.

Third, the foreseen changes in recycling and compliance centred on changes in legislation and the desired outcomes, moving recycling targets and changes in markets. The respondents mentioned the following:

- Ever-tightening restrictions on hazardous chemicals in new EEE products will further limit the viability and demand for recycled materials from WEEE, at least for the manufacture of new EEE.

- Legislative changes that increase compliance targets, the compliance fee mechanism, management of waste streams but do not factor in product weight changes.

- Future markets in by-products. If recycling improves will this impact upon the market? Or will some streams be pushed to one side e.g. plastics.

- Reduced flows of WEEE. If waste flows reduce this could trigger recycling plant closures, as the plant capacity can no longer be met.

- The UK leaving the EU.

Finally, whilst some respondents did share new data regarding product weights and residence times, that helped to check the relevant settings in the WOT model, significant or substantial new data was not provided.

Subsection: Adapting state of the art model to the UK context

The project team identified two extensive lists of CN codes relevant to UK EEE market: WEEE Europe (which has CN codes mapped onto UNU and UK categories, prepared by WEEE Europe in conjunction with REPIC) and WOT (with mappings onto PCC and UNU codes, but no UK categories). These lists have 671 and 762 and CN codes, respectively, of which 292 codes overlap, while the rest are unique to each of the two lists. Combined, the two lists contain 1150 unique CN codes.

Following these findings, REPIC reviewed all the CN codes from the two lists combined, assigning UK codes to the WOT CN codes not on the WEEE Europe list for the first time, and updating the UK codes for the WEEE Europe list (part of which overlaps with WOT). REPIC also indicated possible changes to the CN-UK mapping due to the implementation of Open Scope. This was a difficult and sometimes ambiguous task given the terms used to describe the CN codes and the on-going development of the UK guidance on scope. This assessment is, therefore, on-going.

The analysis of the CN-UK mapping defined by these lists showed that multiple UNU keys map to 2 or more UK categories. Therefore, to convert the WOT model output for POM and WG, which is provided at the UNU level, into 14 UK categories, special mapping protocols are required. The protocols are different for POM and WG, with the latter relying on the former, and both types of protocols are time-varying, which reflects on the evolution of the individual products and aggregate categories with time.

Subsection: Exploring crucial improvements of the model to aid our understanding and have value in policy development in relation to waste legislations.

The current generation of the WEEE quantification tools, such as the WOT model, are based on historic EEE POM and products' residence times (Van Straalen et al., 2016). Although the POM data in these tools captures historic variations in sales and production across a wide range of products, there is no underlying economic model to link these variations with wider socio-economic conditions. Moreover, the residence times are largely static, implying that the results for WG are smooth and do not reflect on year-on-year fluctuations in the WEEE arising observed in the official data. Therefore, the key suggested feature of a new model, which will build on the existing WEEE tools, is the ability to estimate annual fluctuations in POM and WG in response to varying wider socio-economic conditions and specific EEE market conditions in the UK.

The wider socio-economic parameters will include UK's inflation-adjusted GDP per capita, consumer confidence index (CCI), inflation indices (CPI or RPI), number of households, wealth distribution across the population, percentages of households with no or multiple units of a given product, number of businesses owning a given product, etc. The specific EEE market parameters will include inflation-adjusted prices of a given EEE product and other replacement, as well as new market drivers that affect the sales, trends in units' weight and so on, depending on the product.

The model will build on the existing body of qualitative and quantitative research on EEE markets to derive statistical relationships between the socio-economic and market conditions introduced above, and the products' annual sales, stock and residence times. Where the data is not available, the quantifications of the proposed relationships will rely on tailor-made surveys across the EEE sector. The model will first generate POM in the number of units per annum consisting of two components: replacement and changes in the stock. The replacement component is equal to WG, while the stock changes will contribute to the replacement component of POM and WG in future years. The number of units sold will then be multiplied by the weight per unit in accordance with the available information on product weight trends. This will give an estimate for POM and WG in total weight per selected category.

To achieve the best possible description, the model could be configured to operate on the CN or PCC product levels. However, calibrating all the necessary parameters for the hundreds of EEE products described by these codes, especially when it comes to defining variable residence times, would require a considerable effort. Therefore, it is sensible to consider aggregate categories such as UNU keys. The results could then be aggregated to UK14 categories.

Discussion and conclusion

Our research enhances UK e-waste estimations through the adaption of the current EU-wide Waste Over Time (WOT) model for WG. This required special new protocols to be developed that map weight flows from one set of aggregate EEE categories to another. The protocols improve our understanding of how the aggregate EEE categories adopted in the UK and EU relate to the underlying granular product databases in the trade statistics (Eurostat), which includes the time-evolution of the mapping as old products get disconnected and new ones enter the market.

In addition, we provide new insights into the socio-economic parameters that policy makers should take into consideration when setting new targets to enhance overall recycling rates. A wider set of parameters need be taken into consideration, this is due to current forecasting methods being reliant on weight-based calculations of EEE POM and WG. Our gap analysis and survey results indicate disparities between EEE POM, WG and WEEE collected that can trigger an imbalance in National Target setting. Focus areas should include:

- Mass Balance – missing components (e.g. compressors, hard-drives etc.) and changing product weights should be better represented;

- Product lifespan and residency times – more information needs to be gathered from households since current data mostly comes from producers;

- Unreported flows – further insights into second-hand or used EEE, legal and illegal WEEE flows are required.

There results compliment previous industry studies with some similar findings (WRAP, 2011; 2012; 2016). Collecting data, within the areas indicated above, should be prioritised as this would not only provide input into a new dynamic model, but will improve intelligence about the implications of Open Scope, compliance target settings, compliance costs and current and future protocols. Capturing products as they enter the market, their weight and their fates gives insights into EEE POM and WG trends. The collation of product weight, in particular, would also provide the ability to estimate future protocols, e.g. SMW and LDA, or identify the need to develop the new protocols. Accurate information regarding product lifespan and residency times would give much needed insights into time horizons from EEE POM to WG. In addition, gathering further intelligence on unreported flows will identify system losses and possible entry points for unregistered sellers.

These new insights could help redirect the flows of EEE POM and WEEE, e.g. by boosting the demand for secondary materials from WEEE and/or by stimulating growth in the second hand or used EEE sector. The desired outcomes of these investigations are especially important given the UK's Circular Economy and Clean Growth strategy (BEIS, 2017; Defra, 2018), which includes an ambitious target to achieve zero waste by 2050.

In conclusion, we argue that in order to have a more robust understanding of UK EEE and WEEE flows there is a need to move beyond the "one product in and one product out" assumption to include:

- historic production and trade statistics, in combination with product lifespan distributions that can be derived from surveys.
- outputs for EEE POM and WG that are tailored for the 14 UK Categories
- socio-economic factors that reflect consumption trends
- market and technology trends that impact on purchase, weight, end of life patterns, reuse and recycling
- better quantification of the fates of WEEE which are unreported or unknown.

Utilising these assumptions would be beneficial both to practitioners operating in this space and researchers focusing on e-waste estimations regardless of EU member state.

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Supplementary data – special protocol Technical description of the time-varying UNU-UK-EU mapping protocols for POM and WG

Notations

Let us introduce the following notations:

- T_c^i – Net imports (tonnes) for CN code c in year i
- Q_m^i – production (tonnes) PCC code m in year i
- A_m^i – POM (tonnes) for PCC code m in year i
- B_n^i – POM (tonnes) for UNU key n in year i
- C_k^i – POM for UK category k in year i
- D_l^i – POM for EU category l in year i
- $\delta_{c,m}^i$ – binary variable equal to 1 if CN code c maps onto PCC code m in year i, and equal to 0 otherwise (WOT CN-PCC mapping)
- $\sigma_{c,n}^i$ – binary variable equal to 1 if CN code c maps onto UNU key n in year i, and equal to 0 otherwise (WOT CN-PCC-UNU mapping)
- $\omega_{c,k}^i$ – binary variable equal to 1 if CN code c maps onto UK code k in year i, and equal to 0 otherwise (CN-UK mapping provided by REPIC and WEEE Europe)
- $\varphi_{n,l}^i$ – binary variable equal to 1 if UNU key n maps onto EU category l in year i, and equal to 0 otherwise (WOT UNU-EU mapping)
- $\alpha_{m,k}^i$ – fraction of POM for PCC code m mapping onto UK category k in year i
- $\beta_{n,k}^i$ – fraction of POM for UNU key n mapping onto UK category k in year i
- $\gamma_{k,l}^i$ – fraction of POM for UK category k mapping onto EU category l in year i
- $b_{k,n}^i$ – fraction of POM for UK category k mapping onto UNU key n in year i
- $g_{l,k}^i$ – fraction of POM for EU category l mapping onto UK category k in year i
- $(\beta_w)_{n,k}^i$ – fraction of WG for UNU key n mapping onto UK category k in year i
- $(\gamma_w)_{k,l}^i$ – fraction of WG for UK category k mapping onto EU category l in year i

The weight fractions $\alpha_{m,k}^i$ define the intermediate PCC-UK protocol, while the weight fractions $\beta_{n,k}^i$ and $\gamma_{k,l}^i$ define the required UNU-UK and UK-EU protocols for POM.

The weight fractions $b_{k,n}^i$ and $g_{l,k}^i$ define the inverse UK-UNU and EU-UK protocols for POM.

The weight fractions $(\beta_w)_{n,k}^i$ and $(\gamma_w)_{k,l}^i$ define the UNU-UK and UK-EU protocols for WG.

We note that $\delta_{c,m}^i$, $\sigma_{c,n}^i$ and $\omega_{c,k}^i$ are not protocols since each CN code always maps onto single PCC, UNU and UK categories, respectively. Instead, they are binary variables (not fractions/percentages) defining regular mappings of CN codes onto PCC, UNU and UK categories, respectively (labels only, not weights). Likewise, $\varphi_{n,l}^i$ is also a binary variable, defining the UNU-EU mapping.

Net imports T_c^i are known from Eurostat data for trade (CN level), while production Q_m^i is known from PRODCOM data for production (PCC level). Combining the two, and using the CN-PCC mapping defined by the $\delta_{c,m}^i$ binary variables, we get POM on the PCC level:

$$A_m^i = Q_m^i + \sum_c \delta_{c,m}^i \cdot T_c^i$$

Equation 1

The summation is performed over all CN codes. This step is possible because of the assumed uniqueness of mapping from CN to PCC, which is supported by Eurostat product code conversion tables.

All the subsequent steps apart from the UNU-EU mapping require protocols. The reason for this is that from the PCC level onwards, moving towards more aggregate categories like UNU and UK often results in splits of a single PCC code (or UNU key) into multiple aggregate categories. This is contrary to the expectation that the codes on a more detailed level should merge into a single aggregate category. The only exception is the UNU-EU mapping which links each UNU key with a single EU category.

In order to create a protocol, a more detailed set of product categories that underpins the mapping between the two categories linked by the protocol is required. For the PCC-UK protocol the underlying detailed categories are CN codes, while for the UNU-UK protocol PCC codes could be used as the link. The UK-EU protocol mapping relies on the UNU codes.

PCC-UK protocol for POM

Before we can define the PCC-UK protocol, we need to know which PCC codes map on which UK categories. This mapping is defined by the following binary variable, which is based on the underlying CN codes:

$$\zeta_{m,k}^i = \begin{cases} 1, & \sum_c \omega_{c,k}^i \cdot \delta_{c,m}^i > 0 \\ 0, & \text{otherwise} \end{cases}$$

For example, if a PCC code m maps onto two UK categories k_1 and k_2 in year i, we have

$$\zeta_{m,k1}^i = 1, \quad \zeta_{m,k2}^i = 1, \quad \zeta_{m,k}^i = 0 \ \text{otherwise}$$

This PCC code consists of several CN codes with the CN-UK mapping defined by the binary variable $\delta_{c,m}^i$.

The question is how best to approximate the POM for each of these CN codes in order to define the PCC-UK protocol for this particular PCC code. The section below provides a possible approximation.

Approximation for CN-level POM

The total production for PCC code m in year i is Q_m^i. Thus, if the production corresponding to CN code c that belongs to PCC code m in year i, which is unknown, is denoted as $q_{c,m}^i$, the sum of these CN-level productions should add to Q_m^i:

$$Q_m^i = \sum_c \delta_{c,m}^i \cdot q_{c,m}^i$$

Equation 2

Here we used the binary filter $\delta_{c,m}^i$ to ensure only those CN codes that belong to the given PCC code are included.

Now, the net imports for these CN codes are known and are denoted as T_c^i. There are two options depending on the sign of the net imports:

- If $T_c^i \geq 0$, then it is possible that this particular CN code is not produced in the UK, i.e. $q_{c,m}^i = 0$ and all the consumption is met through the imports.

- If $T_c^i < 0$, then it is possible that this particular CN code is not consumed in the UK, i.e. $q_{c,m}^i = |T_c^i|$ and all the production serves to meet he exports.

Both of these cases provide a theoretical minimum for the UK production of a given CN code. Thus, a summation of these lowest possible levels of production across all the CN codes within the given PCC code should not exceed Q_m^i:

$$\sum_{c,\, T_c^i \geq 0} \delta_{c,m}^i \cdot 0 + \sum_{c,\, T_c^i < 0} \delta_{c,m}^i \cdot |T_c^i| \leq Q_m^i$$

Equation 3

If this condition does not hold, it means the CN-level data for trade is inconsistent with the PCC-level data for production, and either the trade or production figures have to be adjusted for the left hand side and right hand side of Equation 1 to match. This could either be done by reducing $|T_c^i|$ for the CN codes with negative net imports, or by increasing Q_m^i for the entire PCC code in question. The latter of the two is the easiest way of correcting the possible inconsistencies between the CN and PCC data, which we are going to adopt here.

Thus, if the condition given by Equation 3 does not hold, we restore the balance between imports, exports and productions by setting

$$Q_m^i = \sum_{c,\, T_c^i < 0} \delta_{c,m}^i \cdot |T_c^i|, \quad q_{c,m}^i = \begin{cases} 0, & T_c^i \geq 0 \\ |T_c^i|, & T_c^i < 0 \end{cases}$$

Equation 4

If the condition given by Equation 3 holds and the inequality sign prevails, it means the lower-end estimate for the production on the CN level given by Equation 4 needs to be upgraded. There is no unique way of doing this based on the existing data. Therefore, we are going to use the simplest approximation that production levels for all CN codes are higher than their respective lower-end estimates in Equation 4 by the same amount Ψ_m^i, which is unique to the given PCC code where the relevant CN codes belong to:

$$q_{c,m}^i = \begin{cases} \Psi_m^i, & T_c^i \geq 0 \\ |T_c^i| + \Psi_m^i, & T_c^i < 0 \end{cases}$$

Equation 5

Plugging this into gives:

$$\Psi_m^i \cdot \sum_c \delta_{c,m}^i + \sum_{c,\, T_c^i<0} \delta_{c,m}^i \cdot |T_c^i| = Q_m^i$$

Therefore, the quantity Ψ_m^i which defines the production on the CN level according to is equal to

$$\Psi_m^i = \frac{Q_m^i - \sum_{c,\, T_c^i<0} \delta_{c,m}^i \cdot |T_c^i|}{\sum_c \delta_{c,m}^i}$$

Equation 6

The CN-level POM for the CN codes corresponding to PCC code m is therefore given by

$$q_{c,m}^i + T_c^i$$

Defining the weights for the PCC-UK protocol for POM

With the CN-level approximation for POM introduced above, we can define the required PCC-UK protocol that maps the POM for PCC code m to UK category k in year i:

$$\alpha_{m,k}^i = \frac{\sum_c \omega_{c,k}^i \cdot \delta_{c,m}^i \cdot (q_{c,m}^i + T_c^i)}{\sum_{k'} \sum_c \omega_{c,k'}^i \cdot \delta_{c,m}^i \cdot (q_{c,m}^i + T_c^i)}$$

Here $q_{c,m}^i$ is either given by or, depending on the outcome of the test provided by:

- If = FALSE, then $q_{c,m}^i$ is given by
- If = TRUE, then $q_{c,m}^i$ is given by (and Ψ_m^i is defined in

The summations are performed over all CN codes and UK categories under consideration.

This methodology applies to all PCC codes that split into multiple UK categories, no matter how many UK categories are involved in the split.[8] The total number of UK codes that the given PCC code m maps onto in year i is given by

$$u_m^i = \sum_k \zeta_{m,k}^i$$

[8] Based on the current mapping, no PCC codes splits into 5 or more UK categories.

To complete defining the protocol, those PCC codes that map onto a single UK category, i.e. those that have $u_m^i = 1$, need to be assigned the weight conversion factor $\alpha_{m,k}^i = 1$, while for the PCC codes not mapping on any of the UK categories, $u_m^i = 0$, we set $\alpha_{m,k}^i = 0$.

Finally, if for a given PCC code m the POM in year i is zero,

$$A_m^i = Q_m^i + \sum_c \delta_{c,m}^i \cdot T_c^i = 0,$$

the corresponding PCC-UK conversion factors should also be set to zero for all k, $\alpha_{m,k}^i = 0$, even if some of the mapping binary variables $\zeta_{m,k}^i$ are non-zero (i.e. PCC and UK "labels" are mapped by the weights are not).

With the PCC-UK protocol defined, the PCC-level POM can be converted into POM in UK categories as follows:

$$C_k^i = \sum_m \alpha_{m,k}^i \cdot A_m^i$$

In this formula the summation is performed over all PCC codes.

All the parameters in these relationships correspond to year i and are expected to be time-variable. For any year i and any PCC code m, however, the following normalising condition holds:

$$\sum_k \alpha_{m,k}^i = \begin{cases} 1, & A_m^i \neq 0 \\ 0, & A_m^i = 0 \end{cases}$$

UNU-UK protocol for POM

Now let us define the UNU-UK protocol. Using the underlying CN codes to provide the splits between the weight flows is not practical for the UNU-UK mapping since POM is not known at the CN level. We cannot possibly rely on the trade data alone (without production) to define the weight splits across as many as 50% of all the UNU keys that map onto multiple UK categories.

Instead, we propose to use the underlying PCC codes that belong both to a given UNU key and to the multiple UK categories which this key splits into. The advantage here is that POM data is available on the PCC level, and the mapping between PCC and UK codes is straightforward for over 95% of PCC codes, while the remainder of the PCC codes with the irregular UK mapping are covered by the newly defined approximate PCC-UK protocol.

Before we can define the UNU-UK protocol, we need to know which UNU keys map on which UK categories. This mapping is defined by the following binary variable:

$$\xi_{n,k}^i = \begin{cases} 1, & \sum_c \omega_{c,k}^i \cdot \sigma_{c,n}^i > 0 \\ 0, & \text{otherwise} \end{cases}$$

We also need to know which PCC codes correspond to a given UNU key. For this purpose, the following binary variable is introduced:

$$\chi_{m,n}^{i} = \begin{cases} 1, & \sum_{c} \delta_{c,m}^{i} \cdot \sigma_{c,n}^{i} > 0 \\ 0, & \text{otherwise} \end{cases}$$

The UNU level POM is therefore given by

$$B_n^i = \sum_m \chi_{m,n}^i \cdot A_m^i$$

The corresponding weight fraction defining the respective mapping of the POM for UNU key n onto UK category k in year i is expressed as follows:

$$\beta_{n,k}^i = \frac{\sum_m \chi_{m,n}^i \cdot \left(\alpha_{m,k}^i \cdot A_m^i\right)}{\sum_{k'} \sum_m \chi_{m,n}^i \cdot \left(\alpha_{m,k'}^i \cdot A_m^i\right)}$$

The summations are performed over all PCC codes and UK categories under consideration.

This methodology applies to all UNU keys that split into multiple UK categories, no matter how many UK categories are involved in the split.[9] The total number of UK codes that the given UNU key n maps onto in year i is given by

$$v_n^i = \sum_k \xi_{n,k}^i$$

To complete defining the protocol, those UNU keys that map onto a single UK category, i.e. those that have $v_n^i = 1$, need to be assigned the weight conversion factor $\beta_{n,k}^i = 1$, while for the UNU keys not mapping only any of the UK categories, $v_n^i = 0$, we set $\beta_{n,k}^i = 0$.

Finally, if for a given UNU key n the POM in year i is zero,

$$B_n^i = \sum_m \chi_{m,n}^i \cdot A_m^i = 0,$$

the corresponding PCC-UK conversion factors should also be set to zero for all k, $\beta_{n,k}^i = 0$, even if some of the mapping binary variables $\xi_{n,k}^i$ are non-zero (i.e. PCC and UK "labels" are mapped by the weights are not).

With the UNU-UK protocol defined, the UNU-level POM can be converted into POM in UK categories as follows:

$$C_k^i = \sum_n \beta_{n,k}^i \cdot B_n^i$$

Equation 7

The summation is performed over all UNU keys.

All the parameters in these relationships correspond to year i and are expected to be time-variable. For any year i and any UNU key n, however, the following normalising condition holds:

[9] Based on the current mapping, no UNU keys splits into 6 or more UK categories.

$$\sum_{k} \beta_{n,k}^{i} = \begin{cases} 1, & B_n^i \neq 0 \\ 0, & B_n^i = 0 \end{cases}$$

UK-EU protocol for POM

The mapping between UNU keys n and EU6 categories l is unique in each year i, and is given by the binary variable $\varphi_{n,l}^{i}$ which is provided by the WOT model.
Here we use EU6+PV as a default set of the target EU categories, but exactly the same mapping procedure could be applied to other types of EU categories (EU6, EU10, EU10+PV) by altering the UNU-EU binary variables $\varphi_{n,l}^{i}$ accordingly.

Before we can define the UK-EU protocol, we need to know which UK categories map on which EU categories. This mapping is defined by the following binary variable:

$$\theta_{k,l}^{i} = \begin{cases} 1, & \sum_{n} \xi_{n,k}^{i} \cdot \varphi_{n,l}^{i} > 0 \\ 0, & \text{otherwise} \end{cases}$$

The corresponding weight fraction defining the respective mapping of the POM for UK category k onto EU category l in year i is expressed as follows:

$$\gamma_{k,l}^{i} = \frac{\sum_{n} \varphi_{n,l}^{i} \cdot \left(\beta_{n,k}^{i} \cdot B_n^i\right)}{\sum_{l'} \sum_{n} \varphi_{n,l'}^{i} \cdot \left(\beta_{n,k}^{i} \cdot B_n^i\right)}$$

The summations are performed over all UNU keys and EU categories under consideration.

The total number of EU categories that the given UK category k maps onto in year i is given by

$$w_k^i = \sum_{l} \theta_{k,l}^{i}$$

To complete defining the protocol, those UK categories that map onto a single EU category, i.e. those that have $w_k^i = 1$, need to be assigned the weight conversion factor $\gamma_{k,l}^{i} = 1$, while for the UK categories not mapping only any of the EU categories, $w_k^i = 0$, we set $\gamma_{k,l}^{i} = 0$.

Finally, if for a given UK category k the POM in year i is zero,

$$C_k^i = \sum_{n} \beta_{n,k}^{i} \cdot B_n^i = 0,$$

the corresponding UK-EU conversion factors should also be set to zero for all l, $\gamma_{k,l}^{i} = 0$, even if some of the mapping binary variables $\theta_{k,l}^{i}$ are non-zero (i.e. UK and EU "labels" are mapped by the weights are not).

With the UK-EU protocol defined, the UK-level POM, which is denoted as C_k^i, can be converted into POM in EU categories as follows:

$$D_l^i = \sum_{k} \gamma_{k,l}^{i} \cdot C_k^i$$

Equation 8

The summation is performed over all UK categories.

All the parameters in these relationships correspond to year i and could be time-variable. For any year i and any UK category k, however, the following normalising condition holds:

$$\sum_l \gamma_{k,l}^i = \begin{cases} 1, & C_k^i \neq 0 \\ 0, & C_k^i = 0 \end{cases}$$

Equation 8 can be used to convert the reported UK-level POM and WEEE collected data into the required pool of EU categories (either EU6, EU6+PV, EU10 or EU10+PV).

Inverse UK-UNU protocol for POM

Following the logic of linking any pair of aggregate categories using their respective mapping on a more granular category, we can introduce the inverses of the UNU-UK and UK-EU mapping protocols.

The weight fraction defining the respective mapping of the POM for UK category k onto UNU key n in year i is expressed as follows:

$$b_{k,n}^i = \frac{\sum_m \chi_{m,n}^i \cdot \left(\alpha_{m,k}^i \cdot A_m^i\right)}{\sum_{n'} \sum_m \chi_{m,n'}^i \cdot \left(\alpha_{m,k}^i \cdot A_m^i\right)}$$

This is the inverse of the UNU-UK mapping protocol with the weights $\beta_{n,k}^i$. Note that the underlying one-to-one mapping between PCC codes and UNU key effectively means that the relevant binary mapping labels $\chi_{m,n}^i$ also act as the mapping weights.

The inverse UK-UNU protocol allows one to convert the UK-level POM into UNU-level POM:

$$B_n^i = \sum_k b_{k,n}^i \cdot C_k^i$$

Equation 9

The summation is performed over all UK categories.

All the parameters in these relationships correspond to year i and are expected to be time-variable. For any year i and any UK category k, however, the following normalising condition holds:

$$\sum_n b_{k,n}^i = \begin{cases} 1, & C_k^i \neq 0 \\ 0, & C_k^i = 0 \end{cases}$$

Combining Equation 9 with, we arrive at the following condition that makes the inverse UK-UNU mapping consistent with the original UNU-UK mapping:

$$C_k^i = \sum_{k'} C_{k'}^i \cdot \rho_{k,k'}^i, \quad \rho_{k,k'}^i = \sum_n \beta_{n,k}^i \cdot b_{k',n}^i$$

Inverse EU-UK protocol for POM

The corresponding weight fraction defining the respective mapping of the POM for EU category l onto UK category k in year i is expressed as follows:

$$g_{l,k}^{i}=\frac{\sum_{n}\varphi_{n,l}^{i}\cdot\left(\beta_{n,k}^{i}\cdot B_{n}^{i}\right)}{\sum_{k'}\sum_{n}\varphi_{n,l}^{i}\cdot\left(\beta_{n,k'}^{i}\cdot B_{n}^{i}\right)}$$

This is the inverse of the UK-EU mapping protocol with the weights $\gamma_{k,l}^{i}$. Note that the underlying one-to-one mapping between UNU key and EU categories effectively means that the relevant binary mapping labels $\varphi_{n,l}^{i}$ also act as the mapping weights.

The inverse EU-UK protocol allows one to convert the EU-level POM into UK-level POM:

$$C_{k}^{i}=\sum_{l}g_{l,k}^{i}\cdot D_{l}^{i}$$

Equation 10

The summation is performed over all EU categories.

All the parameters in these relationships correspond to year i and could be time-variable. For any year i and any EU category l, however, the following normalising condition holds:

$$\sum_{k}g_{l,k}^{i}=\begin{cases}1, & D_{l}^{i}\neq 0\\ 0, & D_{l}^{i}=0\end{cases}$$

Combining Equation 10 with Equation 8, we arrive at the following condition that makes the inverse EU-UK mapping consistent with the original UK-EU mapping:

$$D_{l}^{i}=\sum\nolimits_{l'}D_{l}^{i}\cdot\vartheta_{l,l'}^{i},\quad \vartheta_{l,l'}^{i}=\sum\nolimits_{k}\gamma_{k,l}^{i}\cdot g_{l',k}^{i}$$

Using the UNU-UK protocol for POM to project UNU-level POM and WG from WOT model onto UK categories

To obtain an adequate estimate of WG in the UK categories, we need to apply the UNU-UK protocols for the past years when the sales took place, which are denoted here as t_j, rather than in the current year t_i when the WG is calculated:

$$W_{k}^{i}=\sum_{n}\sum_{j=1980}^{i}\beta_{n,k}^{j}\cdot\mathrm{Weib}\left(t_i-t_j,k_n(t_j),\lambda_n(t_j)\right)\cdot B_{n}^{j}$$

Equation 11

Here $\mathrm{Weib}(\cdot)$ is Weibull distribution for the UNU key n corresponding to sales in year t_j, evaluated in the current year t_i, and the outer summation is performed over all UNU keys.

This expression is different from the more intuitive but incorrect methodology of applying the UNU-UK protocols for the current year t_i when the WG is calculated:

$$\widetilde{W}_k^i = \sum_n \beta_{n,k}^i \cdot \sum_{j=1980}^{i} \text{Weib}\left(t_i - t_j, k_n(t_j), \lambda_n(t_j)\right) \cdot B_n^j$$

The issue with the latter formula is that the POM-based protocols in the current year t_i do not match with the actual protocols of the products that are being discarded as WEEE in this year, since these product originate from earlier years when the protocols were different. This mismatch could lead to errors in the estimated weight per each of the UK categories calculated using UNU figures.

We should, therefore, use the above to work out POM C_k^i and Equation 11 to calculate WG W_k^i in UK categories, based on the historic POM B_n^j in the UNU keys.

UNU-UK protocol for WG

UNU-level WG in year t_i is expressed via the relevant POM and residence time distributions:

$$V_n^i = \sum_{j=1980}^{i} \text{Weib}\left(t_i - t_j, k_n(t_j), \lambda_n(t_j)\right) \cdot B_n^j$$

Equation 12

According to Equation 11, the fraction of this WG that feeds into the UK category k is given by

$$\sum_{j=1980}^{i} \beta_{n,k}^j \cdot \text{Weib}\left(t_i - t_j, k_n(t_j), \lambda_n(t_j)\right) \cdot B_n^j$$

Here $\beta_{n,k}^j$ are historic UNU-UK mapping protocols for POM.

Therefore, the UNU-UK protocol weights for WG mapping are given by

$$(\beta_w)_{n,k}^i = \frac{1}{V_n^i} \cdot \sum_{j=1980}^{i} \beta_{n,k}^j \cdot \text{Weib}\left(t_i - t_j, k_n(t_j), \lambda_n(t_j)\right) \cdot B_n^j, \quad \text{if} \sum_{j=1980}^{i} B_n^j > 0$$

$$(\beta_w)_{n,k}^i = 0, \quad \text{if} \sum_{j=1980}^{i} B_n^j = 0$$

Equation 13

Here V_n^i given by Equation 12.

It is easy to see that the WG protocol weights satisfy the condition

$$\sum_k (\beta_w)_{n,k}^i = 1$$

for all the UNU keys with non-zero POM in any of the historic years (i.e. when the first part of Equation 13 holds).

Using this protocol, one can convert UNU-level WG in year t_i into UK category k WG in the same year according to the following expression:

$$W_k^i = \sum_n (\beta_w)_{n,k}^i \cdot V_n^i$$

UK-EU protocol for WG

Following from the definition of the UK-EU mapping protocol for POM, the weight fraction defining the respective mapping of the WG for UK category k onto EU category l in year i is expressed as follows:

$$(\gamma_w)_{k,l}^i = \frac{\sum_n \varphi_{n,l}^i \cdot \left((\beta_w)_{n,k}^i \cdot V_n^i\right)}{\sum_{l'} \sum_n \varphi_{n,l'}^i \cdot \left((\beta_w)_{n,k}^i \cdot V_n^i\right)}$$

Equation 14

Here V_n^i is WG for UNU key n in year t_i calculated from Equation 12, $(\beta_w)_{n,k}^i$ are the weights for the UNU-UK WG mapping protocol defined in Equation 13, and $\varphi_{n,l}^j$ are the binary UNU-EU mapping variables introduced in the previous sections that also act as mapping weights. The summations are performed over all UNU keys and EU categories under consideration.

Using this protocol, one can convert UK-level WG in year t_i into EU category l WG in the same year according to the following expression:

$$U_l^i = \sum_k (\gamma_w)_{k.l}^i \cdot W_k^i$$

Equation 15

This formula could be used to convert the WEEE figures that are officially reported in UK categories into EU categories.

Equation 14 can be verified by expressing the WG for EU category l in year t_i directly via UNU-level POM:

$$U_l^i = \sum_n \sum_{j=1980}^{i} \varphi_{n,l}^j \cdot \text{Weib}\left(t_i - t_j, k_n(t_j), \lambda_n(t_j)\right) \cdot B_n^j$$

Plugging this into Equation 15, along with the UK-level WG from Equation 11 and the UK-EU WG mapping weights from Equation 14, we should arrive at the same result on both sides.

Small mixed WEEE protocol

Small mixed WEEE (SMW) is defined as WEEE in the UK categories 2 to 10. The SMW protocol provides an estimated conversion of the total mass flow across these categories into each individual UK category (from 2 to 10), which is used to report the collected SMW without having to sort all the items into their respective categories.

The WOT results for WG allow us to estimate the SMW protocol both for the historic years and in the near-term future (based on the underlying UNU-level POM forecasts):

$$(w_{smw})_k^i = W_k^i \cdot \left[\sum_{k'=2}^{10} W_{k'}^i\right]^{-1}, \quad k = 2, \ldots, 10$$

Here W_k^i is the WG for UK category k in year t_i given by Equation 11. The protocol depends on assumptions regarding unit weights as well as residence time distributions made in the WOT model, which affect the estimates for W_k^i.