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Research Paper

The potential impact of the new ‘Right to Repair’ rules on electrical and electronic equipment waste: A case study of the UK

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ABSTRACT

Every year an estimated two million tonnes of waste electrical and electronic equipment (WEEE) are discarded by householders and companies in the United Kingdom (UK). While the UK has left the European Union (EU), its waste-related policies still mirror those of the EU, including the WEEE-related policies. Motivated by the recent introduction the so-called ‘Right to Repair’ policy for electrical and electronic equipment (EEE) across the EU and UK, this paper aims to demonstrate that, depending on the commitment and behavioural changes by the consumers and the government, the future of the WEEE management of the UK will vary. To this end, focusing on landfilled WEEE reduction we develop a generic system dynamics model and apply it to eleven WEEE categories. They depict the flow of EEE and WEEE representing the interaction among the stakeholders (*e.g.*, consumers and producers of EEE) and relevant government regulations of the UK. Our four scenario analyses find that longer use of EEE and better WEEE collection seem to be effective in reducing landfilled WEEE, while more reuse and more recycling and recovery have negligible impacts, despite excluding the additional generation of landfilled WEEE as a result of recycling and recovery. Comparing with the business-as-usual scenario, one year longer EEE use and 10% more of WEEE collection could at maximum reduce landfilled WEEE by 14.05% of monitoring and control instruments and 93.93% of display equipment respectively. Backcasting scenario analyses reveal that significant efforts are required to reduce the targeted amounts.

1. Introduction

How many unused electronic gadgets are lingering somewhere in your home in the UK? Community-level initiatives to address the WEEE problem have been taking place. Examples such as the well-established ReStart Project since 2013 that hosts repairing events for electrical and electronic equipment (EEE) in various locations in the UK (ReStart, n. d.), London Repair Week 2020 and 2022 (ReLondon, n.d.), ‘Tech-Takeback’ pop-up collection scheme in Brighton area (Greenfield, 2021), just to name a few, are representative of people’s efforts and a mind-set to promote using EEE in a more circular manner. Nevertheless, every year an estimated two million tonnes of waste electrical and electronic equipment (WEEE) are discarded by householders and companies in the UK (Health and Safety Executive, n.d.). In addition, UK homes are estimated to be hoarding up to forty-million electrical devices, and younger generations are owing more technological gadgets than older generation (Environtec, 2019). Unless something is done about it the problem of WEEE for the UK, who ranks second only to Norway in generating per-capita WEEE will become worse in the future (Dennis, 2023).

This paper aims to demonstrate that, depending on the commitment and behavioural changes by the consumers and the government, the future of the WEEE management of the UK will vary. Our system dynamics (SD) model depicts the flow of EEE and WEEE representing the interaction among the stakeholders (consumers and producers of EEE, WEEE management agencies and facilities) and relevant government regulations of the UK. This paper serves a different purpose from existing studies of WEEE that employ SD as an analytical method. There are studies that provide SD models from the raw material extraction phase to waste disposal and recycling, to address WEEE management from the perspective of sustainability or circular economy. Due to their large scale and scope these models are applied to one category of electronic waste (Giorgiadis and Besiou, 2009; Elia et al., 2019; Llerena-Riascos et al., 2021; Guzzo et al., 2022). There are also studies that employ SD models to address specific issues associated with WEEE management such as the role of the informal sector and recovery of specific types of

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material, using aggregate WEEE data (Ardi and Leisten, 2016; Deva and Weijden, 2021; Putri and Kusumastuti, 2021). We present an SD model that is on the one hand smaller in its system boundary of the EEE-WEEE flow but on the other hand finer in its contents, tracking the flow of eleven WEEE categories. By conducting analyses using a circular EEE-WEEE system for multiple product categories this study makes a novel contribution to the existing literature, as studies that integrate WEEE management with a sustainability-oriented circular system incorporating various product types are scarce (*cf.* Islam et al., 2021; Sundar et al., 2023). Our SD simulation exercise reveals that focusing on improving the collection rates of WEEE rather than the reuse rates is effective in reducing landfilled WEEE. Our four scenario analyses and a backcasting analysis find that longer use of EEE and better WEEE collection seem to be effective in reducing landfilled WEEE, while more reuse and more recycling and recovery have negligible impacts.

2. Background information

Disappointingly, neither consumers nor producers are not necessarily motivated by the environmental impact of WEEE. Consumers are primarily interested in the functionality of the EEE, and producers perceive environmental requirements as something that reduce their profit margins and EEE reuse markets as potential impediment of sales of new items (Cole et al., 2019a and b). Nevertheless, consumers are willing to engage in repair activities and choose EEE with better repairability, depending on the conditions, *e.g.*, repair cost and repairability information (Šajn, 2022). Producers, however, may need a nudge towards more sustainable practice, in the form of stricter regulatory requirements concerning their products.

The European Union (EU), in which more than sixteen kilogrammes per year of electrical waste per person are generated of which only about forty per cent are recycled (Times of India, 2021), introduced the Right to Repair (RtoR) that came into effect on 1 March 2021. The corresponding ten ecodesign-implementing regulations that launched the RtoR require firms selling home appliances in the EU to make their products last longer and make spare parts available for up to ten years. This requirement applies to ten product categories (European Commission, 2019). The EU's RtoR is part of the Sustainable Product Policy Framework (SPPF) that is one of the implementation instruments under EU's Circular Economy Action Plan (CEAP). Originally published in 2015 (European Commission, 2015), the renewed 2021 CEAP is a commitment to move the EU towards a circular economy and promote a coherent policy framework for product design, production process, consumption, and waste management.

While the UK has left the EU, UK consumers are able to benefit from the EU's RtoR. All manufacturers of EEE that place their product in the EU market must comply with the EU's RtoR for their trade with the EU to continue, as EU ecodesign measures apply to products placed on the EU market, regardless of where they are manufactured (European Commission, 2020b). Accordingly, the UK government introduced the Ecodesign for Energy-Related Products and Energy Information Regulations 2021 (SI 2021 No. 745), a.k.a. the Right to Repair Regulations (henceforth the UK RtoR Regs) that came into force in July 2021 and mirror the corresponding EU regulations. The UK RtoR Regs require EEE manufacturers to provide professional repairers with technical information and spare parts. These spare parts must be made available for minimum periods of seven to ten years after the last unit of the model has been placed on the market, and repairs must be possible using commonly available tools (the House of Commons, 2021). Also relevant is the UK's WEEE targets that mirror those of the EU set by the current WEEE Directive (of 2012/19). The WEEE Regulations of 2013 (henceforth the 2013 WEEE Regs), effective 1 January 2014, replace the 2006 regulations and set the WEEE annual collection target as 65 % of the average weight of EEE placed on the market in the three preceding years.

The key element of the operational side of the WEEE management of the UK under the 2013 WEEE Regs is the Producer Compliance Scheme (PCS). Producers placing over five tonnes of EEE on the UK market are required to join one of the twenty-seven PCSs in the UK (GOV. UK, 2022; the Department for Business, Innovation and Skills (DBIS), 2014). Each producer member of a PCS is responsible for financing a portion (according to market share) of the overall WEEE collection target (as well as treatment, recovery, and environmentally sound disposal) in each of the categories in which they placed EEE on the UK market in the previous compliance year. PCSs must submit evidence to support its declaration of compliance for the proper treatment of WEEE. Only Approved Authorised Treatment Facilities (AATFs) may issue evidence of treatment of WEEE in the UK to a PCS for the amount and type of WEEE delivered to them, and only Approved Exporters (AEs) may issue evidence that whole WEEE has been exported for re-use (DBIS, 2014).

Consumers do not have any obligations under the 2013 WEEE Regs other than participating in the separate collection methods for WEEE available under the PCS. Before 2021 retailers who sold EEE could pay a fee which covered their recycling obligations under the Distributor Take-back Scheme (DTS) operated by Valpak under the 2013 WEEE Regs. Starting 2021, large EEE retailers with a sales turnover of more than £100,000 are required to take back WEEE in-store. Starting 2022 online EEE sellers are also required to provide their own take-back solution or join the DTS.

As WEEE arises from socio-economic interactions among producers and consumers of EEE, regulatory authorities of EEE and WEEE, and agents in charge of the management of WEEE, SD, a computer-aided approach to study complex systems, is ideal for its study. In applying an SD model to the UK for the study of WEEE management, we simulate varying degrees of policy interventions and different behavioural assumptions as 'scenarios'. Scenario analyses inform us the necessary degrees of intervention to achieve specific WEEE targets and deliver a portfolio of effective mitigation strategies for the UK.

3. Material and methods

3.1. The models

We first develop a general SD model that depicts the flow of EEE and WEEE representing the interaction among the stakeholders: consumers and producers of EEE, WEEE collection agents, and WEEE treatment facilities. Then, we introduce the specific structure of the flow of EEE and WEEE of the UK under the 2013 WEEE Regs and applied the SD model to eleven out of fourteen categories of WEEE by changing parameters and functional forms tailored to each category. We excluded 'Automatic Dispensers,' 'Medical Devices,' and 'Photovoltaic Panels' categories due to the lack of their waste flow data and for the fact that these categories constitute only 0.28 %, 0.01 %, and 2.33 %, respectively, for their weights in terms of products placed in the UK market in 2020 (Environment Agency, 2022).

3.1.1. Reference modes

To motivate the set of scenario analyses (see Section 3.2) that we conduct using our SD model we choose WEEE collection rate (tonnes per year) as the reference mode for the current study. Reference modes for an SD model represent how a set of key variables have evolved over time. WEEE collection rate is a flow data (tonnes per year), the amount of household WEEE collected at Approved Authorised Treatment Facilities (AATFs) and approved exporters on their behalf in the UK each year (Environment Agency, 2022). Fig. 1 shows the actual changes in WEEE collection rate by category, standardized by 2008 = 100 (there seem to be unusual changes in 2020 for some categories, which could be due to COVID-19). The SD model we constructed aims to capture this reference mode.

In contrast to the dynamics of WEEE collected shown by Fig. 1, the overall amount of EEE placed on the UK market between 2008 and 2019 remained about the same. For categories such as 'Toys Leisure and Sports' and 'Display Equipment' whose amount of EEE placed on the UK

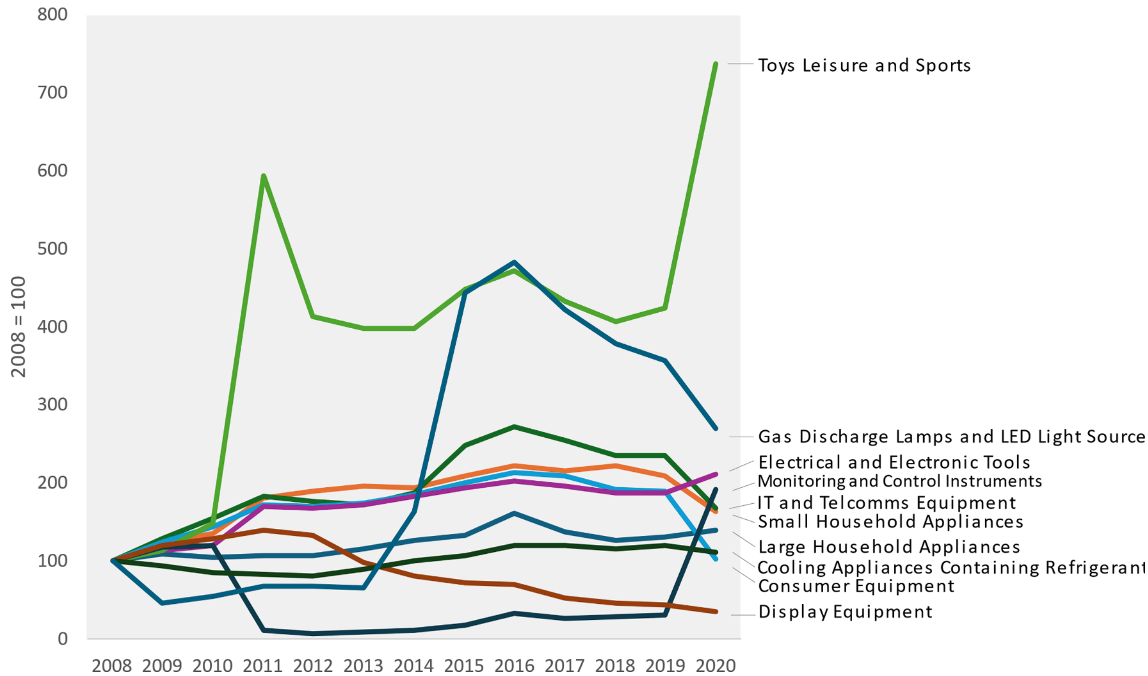

Fig. 1. The amount of WEEE collected every year in the UK by category (2008 = 100). 'Light Equipment' is excluded due to the lack of data. Data: https://www.gov.uk/government/statistical-data-sets/waste-electrical-and-electronic-equipment-weee-in-the-uk.

market decreased between 2008 and 2019, the collection of WEEE seems to have improved.

3.1.2. The conceptual model

Fig. 2 presents the conceptual model capturing the flow of EEE and WEEE in the UK. Consumption of EEE by the consumers is the starting point of the flow of WEEE, and through extending the lifetime of EEE by repairing, the collection of WEEE, and recovery of materials for reuse and recycling, the EEE-WEEE flow can move towards a circular system (Islam et al., 2021).

Unfortunately, some WEEE are not collected but are directly sent to landfills ('WEEE dumped'). Meanwhile WEEE after treatment will take several paths: reuse, recycling, other recovery of materials including energy recovery, or to be transferred to landfills as residual waste. The model separates treated WEEE into two paths: 'reuse' which will put the treated WEEE back into consumers' hands as EEE, and 'recycling and recovery' (excluding reuse) which refers to the treated WEEE that comes back to the economic system as recycled materials and energy, *i.e.*, productive resources. Such (non-virgin) resources can be employed by many sectors, including the producer of EEE and are representative of a circular economy. However, there is no data available as to what percentage of the recovered resources go back into specifically the EEE sector, nor how they may influence the production level of 'New EEE placed in the market'. Therefore, in this model recovered resources are recorded but do not feed back to the EEE-WEEE cycle.

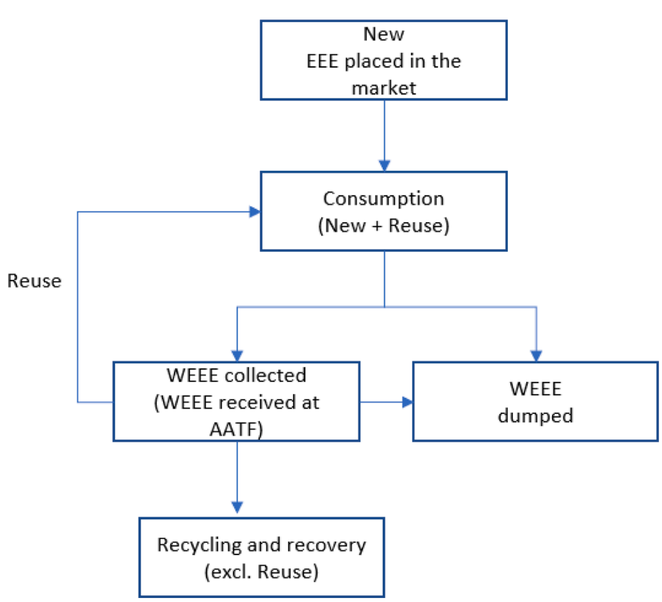

Fig. 2. The conceptual model.

The model does not include the path of export of WEEE. According to the statistics (Environment Agency, 2022), export of WEEE is a negligible amount each year, likely to be due to the UK regulations that restrict the export of WEEE (European Commission, 2020c). Therefore, it is safe to assume that most, if not all, WEEE collected in the UK has been treated within the UK.

3.1.3. System dynamics model

Fig. 3 is a stock-and-flow diagram for the SD model that operationalises the flow of EEE and WEEE represented by Fig. 2. The SD model is applied to all ten categories of WEEE shown in Fig. 1 and also 'Light Equipment', by tailoring the parameters and functional forms (described in Section 3.1.4). There are four stock variables: 'WEEE collected' (in tonnes), 'Household use' (of EEE, in tonnes), 'Dumped WEEE' (in tonnes), and (the number of) 'Households'. This section explains the key equations that underpin the SD model. All the Vensim models are provided upon request for readers to investigate the model structures in detail and replicate the simulation results. Vensim®Professional Version 9.3.0 x64 was used (vensim.com).

The following set of equations define the key relationship among the stock and flow variables of the SD model as represented by Fig. 3. One of the four stock variables (shown inside the boxes in Fig. 3), *Household use* (in tonnes) can inform us how consumers' behaviour towards extending the life of EEE may be evolving. This stock variable represents the accumulation of EEE by households at time *t*, consisting of the set of four flow variables, given the initial value (all measured in tonnes per time period):

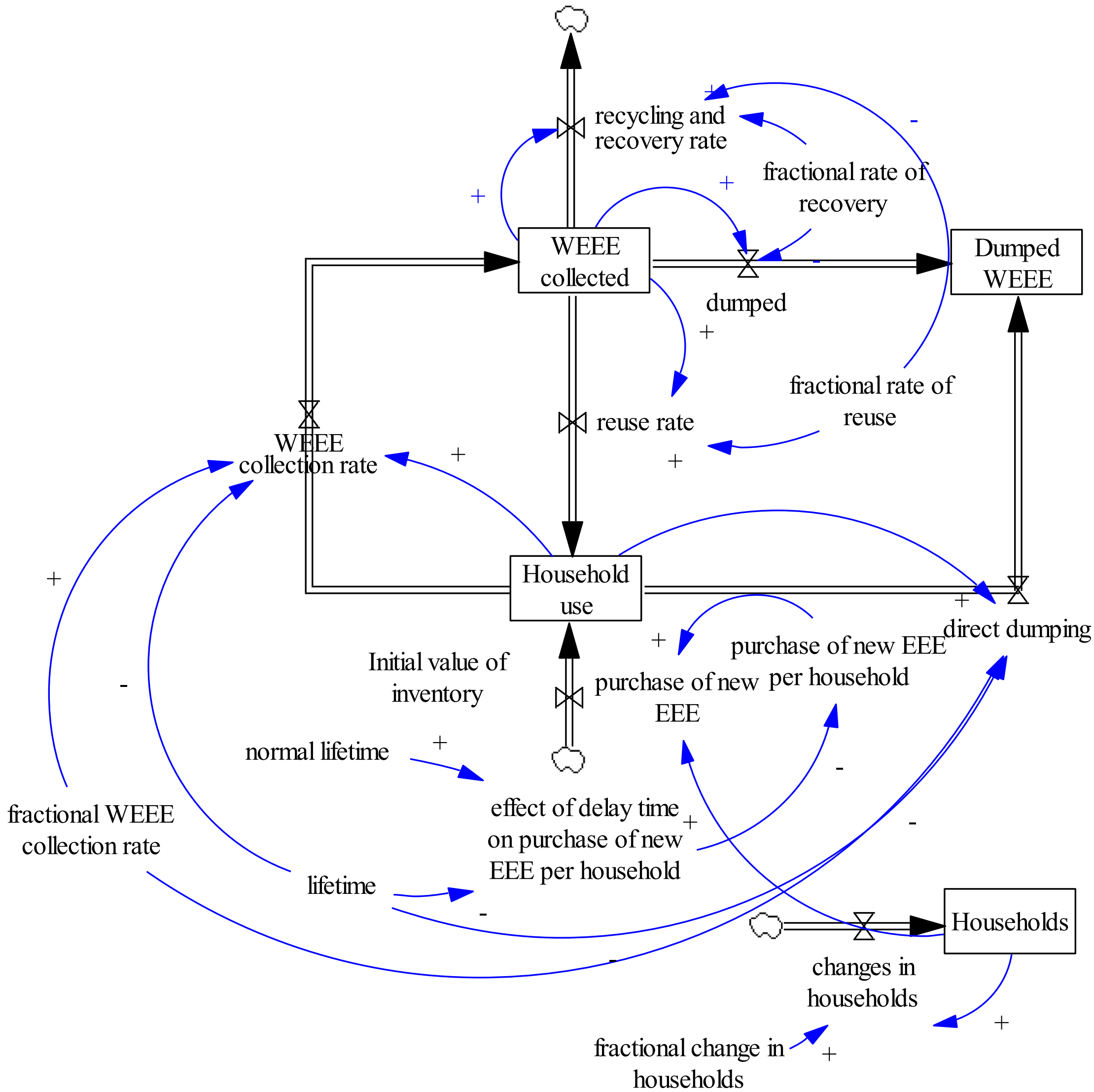

Fig. 3. Stock and flow diagram for the system dynamics model.

$$Household\ use(t) = \int_{t_0}^{t} [purchase\ of\ newEEE(s) + reuse\ rate(s) - WEEE\ collection\ rate(s) - direct\ dumping(s)]ds + Household\ use(t_0) \quad (1)$$

purchase of new EEE is the size of the new EEE market, and *reuse rate* is the amount of the second-hand EEE, in each time period. *WEEE collection rate* and *direct dumpting* represent households' disposal options of WEEE under the 2013 WEEE Regs. The former stands for the flow of household WEEE collected by EEE distributors or Designated Collection Facilities (DCLs) for reuse and recycling, and the latter is the residual disposal of WEEE.

purchase of new EEE (tonnes per year) is a function of *purchase of new EEE per hoursehold* and the number of households (*Households*) which is another stock variable:

The office of National Statistics provides historical data on the number of households in the UK (Office for National Statistics, 2022).

purchase of new EEE per household for any given time period is influenced by households' perception of how long the EEE is anticipated to last, represented by *effect of lifetime on purchase of new EEE per household*. Employing a decision-making structure by (Sterman, 2000), *effect of lifetime on purchase of new EEE per household* in any given time period t can be modelled as

$$effect\ of\ lifetime\ on\ purchase\ of\ new\ EEE\ per\ household = f\left(\frac{normal\ lifetime}{lifetime(t)}\right) = \frac{normal\ lifetime}{lifetime(t)}; f(1) = 1, f' \leq 0 \quad (3)$$

This decision-making structure assumes that the longer the lifetime, the less consumers buy new EEE. Information about anticipated (normal)

$$purchase\ of\ new\ EEE(t) = effect\ of\ lifetime\ on\ purchase\ of\ new\ EEE\ per\ household(t)*purchase\ of\ new\ EEE\ per\ household(t)*Households(t) \quad (2)$$

lifetime of the eleven categories of EEE are obtained from (Cooper, 2005; Cox et al., 2013, Hennines and Stamminger, 2016).

Fig. 3 shows that *purchase of new EEE* is also influenced by the delaying behaviour of households. *Effect of delay time on purchase of new EEE per household* is derived from the product life cycle or lifetime of a product estimates based on existing studies (Cooper, 2005; Cox et al., 2013, Hennines and Stamminger, 2016).

The stock variable *Households*(t) is a simple function:

$$Households(t) = \int_{t_0}^{t} changes\ in\ households(s)ds + Households(t_0) \tag{4}$$

where *changes in households* (tonnes per year) is given by

$$changes\ in\ households(t) = fractional\ change\ in\ households(t)*Households(t) \tag{5}$$

The second variable on the right-hand-side of equation (1), *reuse rate*(t) (tonnes per year), is a performance indicator for the effectiveness of the 2013 WEEE Regs in stimulating repairing activities of EEE. It is defined as follows:

$$reuse\ rate(t) = fractional\ rate\ of\ reuse(t)*WEEE\ collected(t) \tag{6}$$

where *fractional reuse rate*(t) is the percentage of *WEEE collected* that are processed to be reused.

The stock variable *WEEE collected* is intricate: once collected, there are three possible outgoing flows: it can be processed for recovery and recycling, repaired for reuse, or being discarded as residual waste (all in tonnes per year):

$$\begin{aligned} WEEE\ collected(t) = \int_{t_0}^{t} [&WEEE\ collection\ rate(s) - reuse\ rate(s) \\ &- recycling\ and\ recovery\ rate(s) - dumped(s)]ds \\ &+ WEEE\ collected(t_0) \end{aligned} \tag{7}$$

WEEE collection rate is a performance indicator for the effectiveness of the WEEE collection mechanism under the 2013 WEEE Reg. Following Miao et al. (2020), *WEEE collection rate* is defined as a smooth function of the *Household use*(t) given by Equation (1) and the waste delay:

$$WEEE\ collection\ rate(t) = frational\ WEEE\ collection\ rate(t)*SMOOTH(Household\ use(t), lifetime) \tag{8}$$

WEEE collection rate is estimated from the data by the Environment Agency (Environment Agency, 2022) and the European Union (European Union, n.d.).

Finally, *recycling and recovery rate*(t) for equation (7) is given by

$$recycling\ and\ recovery\ rate(t) = (fractional\ rate\ of\ recovery(t) - fractional\ rate\ of\ reuse(t))*WEEE\ collected(t) \tag{9}$$

While ‘recovery’ in the statistics used in this study includes treatment for re-use, recycling and other recovery (European Union, 2019), we separated reuse rate from the rest of recycling and recovery as it is of our main concern.

3.1.4. Parameter estimates and model tests

As there is no single test or method that can prove an SD model to be correct, a variety of model tests for SD have been proposed to uncover flaws and improve models (Sterman, 2000). Sterman (2000) proposed twelve of such tests for the assessment of our dynamic models. We particularly focused on six tests (boundary adequacy, structure assessment, and dimensional consistency, parameter assessment, behavioural reproduction, and family member tests). Here we describe three of the tests used that are helpful in conveying how model tests can help building confidence in the soundness of the baseline model: parameter assessment, behavioural reproduction tests, and family member tests.

Parameter assessment is a procedure and a test to identify parameters to be used in a model (Sterman, 2000). It can be a combination of statistical and judgmental methods. While a parameter can be estimated with a linear equation using ordinary least squares, a linear equation is not reasonable if it leads to an unreasonable number (*e.g.*, a number greater than 1 for a fractional rate, which supposed to be between 0 and 1). Hence, parameters cannot simply be estimated based upon a fitness measure (*e.g.*, R2). In our baseline model there were some parameters and functional forms that needed to be estimated. The assessment criterion for the chosen parameters and functional forms is that the baseline model as a result should capture the reference modes (‘WEEE collected’) along with reflecting the reality when the relevant data are available (see the Vensim models for the full description of the parameters and functional forms).

A behaviour reproduction test examines if the model reproduces the behaviours of interest, or reference modes (Sterman, 2000). In this study, the reference modes are the amounts of WEEE collected every year in the UK by category (Fig. 1) and can be tested using statistics, *e.g.*, Mean Absolute Percent Error (MAPE), as reported in Fig. 4. MAPE can be calculated as (dimensionless; multiply 100 for %)

$$MAPE = \frac{1}{n}\sum \frac{|X_m - X_d|}{X_d} \tag{10}$$

where $n(= 13,\ from\ 2008\ to\ 2020)$, X_d, and X_m are respectively the number of data points, historical data, and model output. The reported MAPEs range from 0.055 (‘1. Large household appliances’) to 0.931 (‘13. Gas Discharge Lamps and LED Light Sources’). In evaluating our model’s ability to replicate historical data, a MAPE up to 0.25 (which corresponds to nine out of the eleven categories reported in Figure 5) can be considered acceptable accuracy (Swanson, 2015). In addition, graphical presentation comparing the estimates and historical data is informative when historical data fluctuate significantly due to factors unexplained by the model. As shown in Fig. 4, while the MAPE for ‘13. Gas Discharge Lamps and LED Light Sources’ is relatively high (0.931), the curvatures of the historical and estimated lines are comparable to some degree (*i.e.*, it increased rapidly for the first ten years or so, followed by a sudden drop).

Finally, family member tests ask whether a model can generate the behaviour of the other similar cases (Sterman, 2000). Because this study applied the generic model (Fig. 3) to all eleven categories of ‘WEEE collected’, MAPE and comparison of the curvatures in Fig. 4 provide the information about the applicability of the generic model. Given Fig. 4, overall, we conclude that our baseline model can be used as the generic model that can be applied to all categories of WEEE. However, it should be noted that while ‘11. Display Equipment’ model might require a

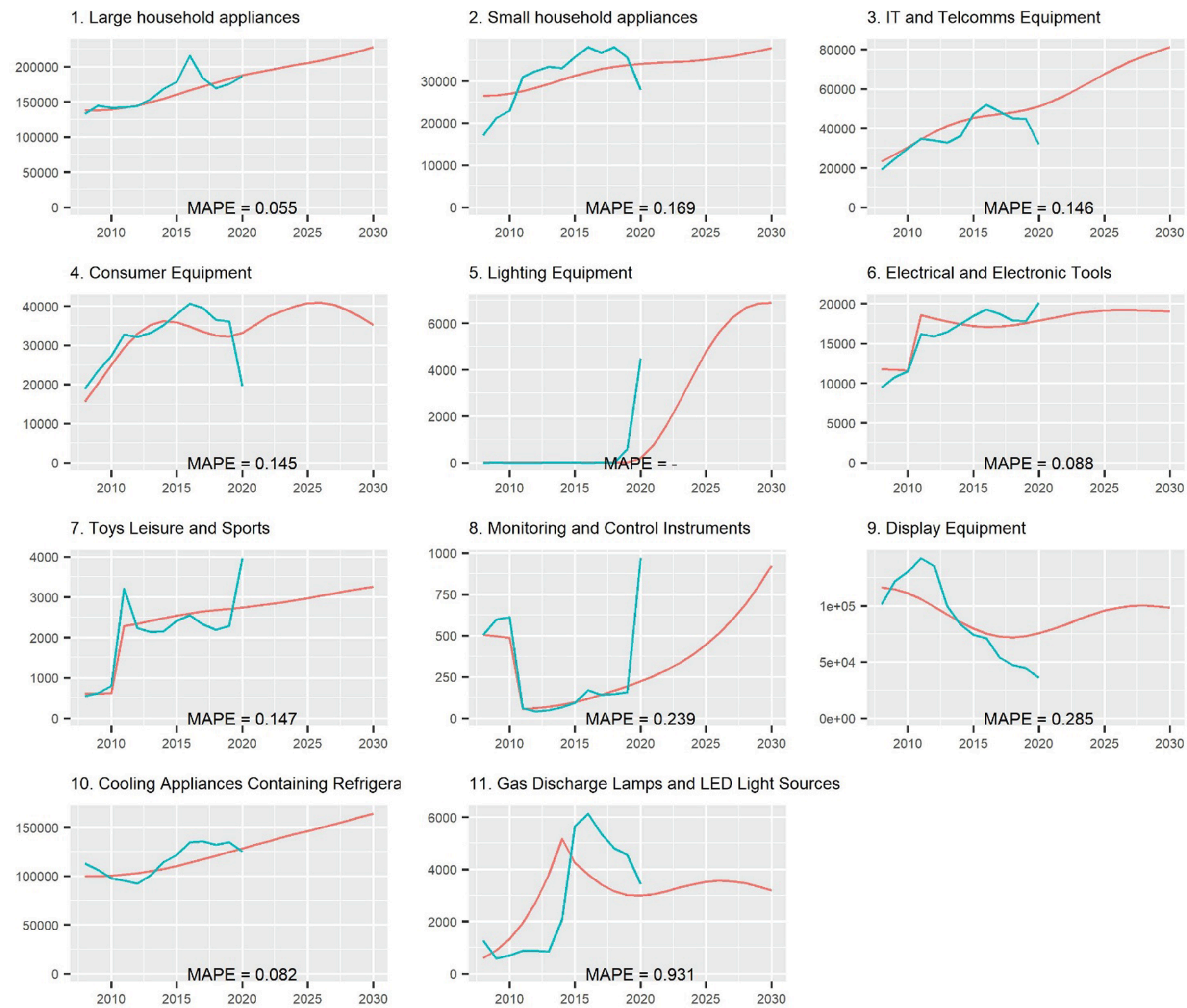

Fig. 4. The comparison of the WEEE collected (in tonnes) every year between the simulation estimates and historical data. Green curves are for historical data while red curves are for estimates obtained from the models. MAPE for '5. Lighting Equipment' cannot be computed due to the lack of data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different model structure. While we expected that the amount of WEEE collected is always smaller than the amount of EEE placed on the market and reuse, it is not the case for some years for this category. We were not able to further investigate this point for the lack of data to address this issue. Further studies await.

3.2. Model analyses

Among various waste-prevention assessment indicators (Watson et al., 2013; Yano and Sakai, 2016), for our analyses we choose the total amount of WEEE dumped in landfill because landfilled WEEE is the worst path in terms of environmental impacts of WEEE disposal (Ikhlayel, 2017). The changes in the total amount of landfilled WEEE is captured by our model. It is computed as a difference between the amount without any policy intervention, *i.e.*, business as usual (BAU) and the amount with intervention measures (m_i, i for measures explained below), defined as

$$\text{Changes in landfilled WEEE} = \frac{\int_{t_1}^{t_2} \left(\text{Dumped WEEE}^{m_i}(s) - \text{Dumped WEEE}^{BAU}(s)\right)ds}{\int_{t_1}^{t_2} \text{Dumped WEEE}^{BAU}(s)ds} \quad (11)$$

where t_1 and t_2 are respectively 2026 and 2030. As explained below, in our simulation analyses we assume that intervention measures take place from 2025.

We conducted two types of model analysis. Firstly, there are sensitivity analyses to assess how improvement in certain parts of the system performance (*e.g.*, the fractional WEEE collection rate in Eq. (3) can reduce the total amount of WEEE dumped in landfill. Secondly, there are backcasting scenario analyses. Backcasting scenarios are drawn to achieve a predetermined target, *e.g.*, a desirable state of the society in future (Kishita et al., 2016). Using an optimisation technique, we identified the amount of effort to achieve a targeted reduction of the total amount of WEEE dumped in landfills. We use the landfilled WEEE as the indicator to assess the performance of the WEEE collection system (there are other indicators; for example, Watson et al. (2013) propose twelve indicators for WEEE prevention). We focus on the landfilled WEEE because of the significant negative effect of landfilling (Baxter et al., 2016; Ikhlayel, 2017), and also because landfilled waste is representative of the final,

Table 1
Sensitivity of WEEE landfilled to improvements in key parameters.

		BAU			Sensitivity							
					Lifetime (+1 year)		WEEE Collection (+10 %)		More Reuse (+10 %)		More Recycling and Recovery (+10 %)	
		tonnes	Fractional WEEE collection rate	Lifetime (years)	tonnes	% change	tonnes	% change	tonnes	% change	tonnes	% change
1	Large Household Appliances	2,427,560	0.309	7.50	2,318,200	−4.50	2,084,960	−14.11	2,425,820	−0.07	2,427,040	−0.02
2	Small Household Appliances	711,890	0.203	7.45	679,680	−4.52	622,790	−12.52	711,840	−0.01	711,890	0.00
3	IT and Telcomms Equipment	50,178	0.417	4.74	47,570	−5.20	12,804	−74.48	50,103	−0.15	50,178	0.00
4	Consumer Equipment *	0	0.589	5.33	0	0.00	0	0.00	0	0.00	0	0.00
5	Lighting Equipment	728,833	0.031	6.25	683,063	−6.28	652,868	−10.42	728,832	0.00	728,833	0.00
6	Electrical and Electronic Tools	268,661	0.263	7.00	256,491	−4.53	232,291	−13.54	268,631	−0.01	268,661	0.00
7	Toys Leisure and Sports	290,019	0.051	4.00	259,209	−10.62	259,949	−10.37	289,989	−0.01	290,019	0.00
8	Monitoring and Control Instruments	213,224	0.015	6.47	183,268	−14.05	191,628	−10.13	213,223	0.00	213,224	0.00
9	Display Equipment	58,979	0.894	8.83	57,154	−3.09	3,579	−93.93	58,956	−0.04	58,979	0.00
10	Cooling Appliances Containing Refrigerants	591,230	0.567	9.63	572,580	−3.15	454,830	−23.07	591,200	−0.01	591,230	0.00
11	Gas Discharge Lamps and LED Light Sources	11,934	0.592	6.47	11,396	−4.50	9,012	−24.48	11,933	−0.01	11,934	0.00
	Total**	5,352,508	–	–	5,068,611	−5.30	4,524,711	−15.47	5,350,527	0.00	5,351,988	−0.01

* Consumer equipment is zero as it is expected that they will be fully recovered by 2025.
** Total amount of WEEE dumped from 2026 to 2030.

dead-end stage of a linear economy.

More specifically, we conducted the following set of sensitivity analyses to simulate the impact of each of the following changes on the total amount of WEEE dumped in landfill in comparison with the corresponding amount without the changes (BAU).

Scenario 1 (Longer Lifetime): product lifetime extends by one year from 2025.
Scenario 2 (More WEEE Collection): the fractional rate of WEEE collection improves by 10 % points from 2025 as long as there is room to improve.
Scenario 3 (More Reuse): the fractional rate of reuse improves by 10 % points from 2025 as long as there is room to improve. Additional reuse will be assumed to replace purchasing of a new product.
Scenario 4 (More Recycling and Recovery): the fractional rate of recovery improves by 10 % points from 2025 as long as there is room to improve.

In addition, our backcasing scenario analyses explore the degree of efforts required to achieve the targeted reduction of the total amount of WEEE dumped in landfills. We employed the Powell hill climbing algorithm (Ventana Systems, n.d.) to find the required changes in prevention measures (*e.g.*, lifetime and WEEE collection) in place from 2025 to achieve the target. Although it may seem highly ambitious, we studied 20 % and 50 % reduction in the total amount of WEEE landfilled as potential targets.

4. Results

4.1. Sensitivity analyses

Table 1 shows the sensitivity of WEEE dumped in landfills to improvements under the four scenarios (longer lifetime, more WEEE collection, more reuse, and more recovery). The sensitivity was measured by the differences in WEEE dumped in landfills with and without improvements from 2026 to 2030.

Table 1 shows variations both by type of improvement and by EEE category (notice that ‘Consumer Equipment’ is unaffected regardless of the type of improvement because the initial BAU values are anticipated to be 0 % by the beginning of the simulation period). Both longer lifetime and more WEEE collection effectively reduce the WEEE landfilled by − 5.30 % and − 15.47 %, respectively. Disappointingly, the impacts of more reuse and more recycling and recovery in reducing the amount of WEEE landfilled, however, are comparatively small. In other words, focusing on the consumption-to-collection arrow in Fig. 2 is more effective than enhancing the ‘reuse’ and ‘recycling and recovery arrows’ that comes out of the collection box in Fig. 2.

The effects of increasing reuse of EEE on reducing the WEEE landfilled, as demonstrated by our simulation results, are weak. The reason why there is little impact of a higher reuse rate on landfilled WEEE in our analysis is because the initial BAU reuse rates are so low–approximately 3 % on average (Environment Agency, 2022). A 10 %-point increase means the reuse rate becomes 13 %–still too small a change to matter. ‘Recycling and recovery’ is another channel to reduce the WEEE landfilled. Ironically, the impacts of increasing recycling and recovery rates are small again due to the already-too-high rates under the BAU scenario, 91 % on average (Environment Agency, 2022). There is little room for noticeable improvements as the current recovery rate is so high. Four of the eleven product categories have less than 10 % remaining to improve, and seven products will be fully recovered when the recovery improves at the current pace. To summarise, our analyses imply that, for governmental policies that aim to enhance product reuse to have significant effects on reducing landfill waste, there must be significant increases in reuse rates. Meanwhile recycling and recovery activities have already reached the point where further reduction in landfilled waste must be achieved through different channels.

Longer lifetime and more WEEE collection affect the generation of WEEE at the beginning of the waste hierarchy represented by the EEE consumption-WEEE collection arrow in Fig. 2 and are more effective in reducing landfilled e-waste. Concerning the impact of a one-year

Table 2
Required effort of improving WEEE collection (the required increase in the WEEE collection rate) to reduce the landfilled WEEE. The amounts of WEEE are for the last five years (*i.e.*, 2026 to 2030) right after the efforts take place.

		BAU		Scenario				
				20 % reduction		50 % reduction		Annual target increase from 2021 to 2022 set by Defra, for comparison***
		tonnes	As of 2025	required additional effort	difference (tonnes)	required additional effort	difference (tonnes)	
1	Large Household Appliances	2,427,560	30.90 %	14.16 %	−485,267	35.36 %	−1,213,765	1 %
2	Small Household Appliances	711,890	20.30 %	15.97 %	−142,300	39.91 %	−355,945	11 %
3	IT and Telcomms Equipment*	50,178	80.35 %	2.37 %	−10,036	3.60 %	−15,261	13 %
4	Consumer Equipment**	0	100 %	–	–	–	–	–
5	Lighting Equipment	728,833	4.10 %	19.19 %	−145,798	47.95 %	−364,329	11 %
6	Electrical and Electronic Tools	268,661	26.30 %	14.76 %	−53,687	36.90 %	−134,332	14 %
7	Toys Leisure and Sports	290,019	5.10 %	19.25 %	−58,003	47.87 %	−144,990	12 %
8	Monitoring and Control Instruments	213,224	1.50 %	19.74 %	−42,635	49.31 %	−106,612	16 %
9	Display Equipment	58,979	89.40 %	2.13 %	−11,798	5.32 %	−29,484	0 %
10	Cooling Appliances Containing Refrigerants	591,230	56.70 %	8.67 %	−118,250	21.68 %	−295,714	4 %
11	Gas Discharge Lamps and LED Light Sources	11,934	59.20 %	8.17 %	−2,387	20.42 %	−5,968	3 %
	Total	5,352,508			−1,070,160		−2,666,400	

* IT and Telcomms Equipment cannot improve its fractional WEEE collection rate to achieve 50% reduction as 100 % collection rate is not enough to reduce by 50%.
** Consumer equipment is zero as it is expected that they will be fully recovered every year by 2025.
*** Source: Langlay (2022).

increase in product lifetime, its impact differs significantly by category. For products for which a one-year extension constitutes a larger percentage of its BAU lifetime such as 'Monitoring and Control Instruments' and 'Toys Leisure and Sports' the impact tends to be higher (−14.05 % and − 10.62 %, respectively). Whereas the reverse is true for categories with the lowest reduction rates (−3.09 % for 'Display Equipment' and − 3.15 % for 'Cooling Appliances Containing Refrigerators'). Concerning the effects of higher WEEE collection rates, this is the channel that can generate a large impact on WEEE management. Our simulation results also show that, in contrast to the case of 'Recycling and recovery' channel, a 10 %-point increase (*e.g.*, from 10 % to 20 %, not 10 % to 11 %) in WEEE collection will have a higher impact when the baseline WEEE collection rate is high, for example, 0.894 for 'Display Equipment' (−93.93 % reduction) versus 0.015 for 'Monitoring and Control Instruments' (−10.13 % reduction). This is due to the generally high 'Recycling and recovery' rates. Once WEEE are collected there already is a strong channel to reduce residual waste to be sent to landfill. Hence, the more WEEE collection rate improves, the larger its additional improvement's impact becomes.

4.2. Backcasting scenario analyses

Table 2 reports backcasting scenario analyses to estimate the required effort of improving the fractional WEEE collection rate to achieve targeted reductions of the landfilled WEEE (as specified by Eq. (11) for our system) by 20 % and 50 % for the last five years (2026 to 2030), for each product category. We chose the fractional WEEE collection rate as the previous sensitivity analyses revealed that the impact of improving reuse and recovery is limited.

To achieve the 20 % reduction target, the required increase in the WEEE collection rate ranges from 2.13 % for 'Display Equipment' to 19.74 % for 'Monitoring and Control Instruments'. The required increase in the collection rate for achieving the 50 % target ranges from 5.32 % for 'Display Equipment' to 49.31 % for 'Monitoring and Control Instruments'. In other words, the higher the initial (BAU) collection rate is, the lower the required effort is to achieve the target. (3.60 % for 'IT and Telcomms Equipment' cannot improve its fractional WEEE collection rate to achieve 50 % reduction as 100 % collection rate is not enough to achieve this target.) As in the previous sensitivity analyses, the degree of efforts to achieve the same target reduction significantly differ by products. For comparison, the recent annual targets of increases in the collection rates issued by Defra are included in Table 2.

5. Discussion

The methodological uniqueness and strength of this study are, firstly, to build a generic SD model explaining the dynamics of EEE and WEEE by category and, secondly, to apply to all the product categories of WEEE for which data is available (except for three categories that lack sufficient data). The models cover eleven categories that jointly account for 97.39 % of EEE placed in the UK market in 2020 by weight. In adopting SD to study the flow and management of WEEE, we have treated WEEE as a single type (Ardi and Leisten, 2016; Miao et al., 2020) or focused on a specific type(s) (Dasgupta et al., 2017; Fan et al., 2018; Sinha Khetrival et al., 2012; Sinha et al., 2016). The behaviour reproduction test using the MAPE and the family member test (Fig. 4) demonstrates the generalisability of the generic model, though application to other areas is needed to confirm this point. The comprehensive approach chosen for this study enables us to elicit detailed WEEE management implications, highlighting differences across product categories. Our simulation results reveal variations among product categories in terms of the sensitivity to different types of improvements in EEE consumption behaviour and WEEE collection and processing (Table 1) and the required improvements in collection rates to reduce landfilled waste (Table 2).

5.1. What measures are critical?

The sensitivity analyses reveal three interesting findings: critical importance of efforts by households, the differences by category, and the limited contributions of better reuse. Firstly, the impacts of longer use of EEE and better WEEE collection differ significantly by product category (Table 1). For example, more than 100,000 tonnes of reduction in landfilled WEEE are predicted for 'Cooling Appliances Containing Refrigerants' (via better WEEE collection) and 'Large Household Appliances' (in both scenarios). In the case of 'Display Equipment' the resulting reduction in landfilled waste is predicted to be substantial in the case of better WEEE collection (93.93 %) but quite small in comparison in the case of longer use (3.09 %), and (to a lesser extent but) likewise pattern is observed for 'Cooling Appliances Containing Refrigerants' and 'Gas Discharge Lamps and LED Light Sources' (23.07 % versus 3.15 % and 24.48 % versus 4.5 %, respectively). Therefore, policymakers may focus on these high-impact categories and scenario(s), while taking account of the potential differences in the difficulty of consumers' cooperating WEEE collection and using EEE longer by product category.

Secondly, among the four interventions, longer use of EEE and better WEEE collection seem to be effective in reducing landfilled WEEE, while more reuse and more recycling and recovery have negligible impacts (Table 1). While increasing recycling and recovery of materials (and to some extent enabling reuse of EEE) are primarily matters of industries (*e.g.*, better product designs by EEE producers and adoption of better recycling technologies by waste processing businesses), extending product lifetime of EEE and increasing WEEE collection require not only EEE producers' contribution (by making EEE more repairable) but also behavioural changes of households. Our findings highlight the need for households' willingness to use EEE longer and dispose WEEE properly via in-store collection, the Distribution Take-Back Scheme upon the purchase of a new product (Department for Business, Innovation and Skills, 2014), and/or requesting the collection service of the local authority for bulky products.

Finally, contrary to the expectations in the emerging notion of circular economy in which reuse is one of the core principles (Kirchherr et al., 2017), our model predicts that the effect of the improvement in reuse (*i.e.*, using a second-hand product) on the reduction of landfilled WEEE is rather small. Also, while in our Scenario 3 an increase in reuse replaces the purchase of new products, if instead reuse were to take place as additional consumption of EEE by households, increases in reuse have a potential to increase the landfilled WEEE–a 'rebound' or 'boomerang' effect of reuse. Studies such as the one by Corvellec et al. (2022) point out the unclear contributions of the circular economy to sustainability. A recent study by Hischier and Böni (2021) finds that, from an environmental perspective, only products whose environmental impact happens primarily in the production phase are worth reusing regardless of their product age. A recent survey indicates consumers' increasing interests in reusing products in general, with 80 % of the respondents wanting to have a charity reuse shop in their neighbourhood; however, the product categories with highest interests in reusing are not EEE but books, clothes, and furniture (Vaclavova, 2022). Nevertheless, our scenario analysis and the simulation result allow for the possibility of contributions of reuse to a sustainable society and make a novel contribution to the emerging literature about repair & reuse which does not yet provide concrete estimates of the effect of repair-and-reuse of EEE on the WEEE management (Odeyingbo et al., 2022). Our results highlight the benefit of conducting a quantitative systems analysis to reveal the risk of taking any particular waste management approach as a panacea (Baxter et al., 2016; Korhonen et al., 2018).

5.2. How much effort should they make?

The backcasting scenario analyses explore the extent of efforts of improving WEEE collection required to achieve targeted reductions of the landfilled WEEE. The results reported in Table 2 show the variations of the required efforts by category to achieve 20 % and 50 % reductions over a five-year period. For example, for 'Display Equipment' a small increase of 2.13 % in the collection rate (from 89.40 % to 91.53 %) would suffice to achieve the 20 % reduction of landfilled waste for this category. Meanwhile, more than 19 % increases in the collection rates would be necessary for 'Toys Leisure and Sports', 'Monitoring and Control Equipment' and 'Lighting Equipment, and almost a 16 % increase for 'Small Household Appliances', to achieve the 20 % reduction in landfilled waste. The 20 % reduction of landfilled waste in these categories also make notable differences in terms of volume (142,300 tonnes for 'Small Household Appliances', 145,798 tonnes for 'Lighting Equipment', for example, compared with 11,798 tonnes for 'Display Equipment'.

Along with 'Display Equipment', categories such as 'Large Household Appliances' and 'Refrigerants' (whose 20 % reduction will result in relatively large volumes of landfilled waste reduction of 485,267 tonnes and 118,250 tonnes, respectively) include products that, upon delivery of a new product, comes with an offer of collecting the old equipment on a like-for-like basis, or households may contact local recycling centre or waste management company. On the one hand, the well-established collection alternatives are available, but not for free. On the other hand, large items are comparatively difficult to dump illegally or inappropriately (they cannot be tossed into waste bins). The combination of these factors may result in 54,000 tonnes of fly-tipping of white goods in England (GOV.UK, 2021a), and Defra's recent annual collection increase targets for these categories (Table 2) are very low.

In contrast, 'Small Household Appliances' and 'Toys Leisure and Sports' (also to some extent 'Monitoring and Control Equipment') include small gadgets such as game extension codes, torches, consoles, and e-cigarettes (GOV.UK, 2021b). Proper disposal of such small items depends primarily on individual households' active efforts. The sorting of recyclable waste from residual (landfilled) waste by households is voluntary in the UK with no penalty or fines for not doing so, and small electric gadgets are easy to toss into the 'landfill waste' bins instead of taking them to the designated bins in public space (*e.g.*, parking areas and kerbsides). In response to the most recent WEEE collection targets issued by Defra (see Table 2), increasing the collection of small mixed WEEE (SMW) including small household appliances, IT and communications equipment, powered tools, toys, control instruments, and smoke detectors has been identified as particularly challenging (GOV.UK, 2017; Langley, 2022). Therefore, how to promote households to make additional efforts in sorting SMW is an important focal area for policymakers. Also critical is the method of WEEE collection in order to preserve the quality of the collected materials. Lamentably, consumers' lack of knowledge about proper discarding method of WEEE has been identified as one of the most significant barriers against the circular WEEE management in the UK (Sundar et al., 2023).

5.3. Limitations of this study

As Sterman (2000) asserts, 'all models are wrong (p. 851)' in that there exists the limitations of model specification, validation, and verification. Firstly, potential impacts of reused EEE and recycled WEEE materials on reducing the need for virgin resources are outside the scope of this study, even though reducing such need is the critical benefit of reuse, material recovery and recycling activities in view of sustainability (*cf.* Hischier and Böni, 2021). As shown by Figs. 2 and 3 such potential impacts are outside the boundary of our SD model. The main reason for our focusing exclusively on the landfilled WEEE and drawing the boundary of our model in this manner is due to the lack of data on how recovered and recycled materials from WEEE are utilised in various sectors of the economy. The identification of potentially useful data is a contribution of our model analyses to help policymakers consider what data collection should be prioritised given the limited resources. Also critically lacking is the data about the stockpiling of EEE by households which prevent reusable resources from EEE to go back into the production-consumption cycle.

Secondly, concerning the 'reuse' channel, the limitation of our models that may affect the impact of a higher reuse rate on landfilled WEEE is that they do not differentiate the product lifetimes between a new product and a second-hand product before a product becomes WEEE (again), albeit it is likely that the former has a shorter product lifetime than the latter does. Our analyses also do not impose a limit on how many times a product can go through the EEE-WEEE reuse cycle (*cf.*

Odeyingbo et al., 2022). The models also assume that recovered and recycled WEEE are not to be taken to the landfill, without taking account of the possibility of non-compliant treatment, illegal dumping or illegal management of WEEE, or additional landfilled WEEE potentially generated as a result of recovery and recycling activities. These limitations of the models may overstate the overall contribution of 'recycling and recovery' channels in reducing landfilled WEEE and obfuscate the relative strength of the two channels. Nevertheless, our findings highlight the need to examine the potential impacts of alternatives to reduce landfilled WEEE carefully. Our results also demonstrate the usefulness of SD analyses and encourage a cautious approach to the implications of concepts such as circular economy on sustainability and WEEE management (Corvellec et al., 2022).

6. Conclusion

Despite that EEE have benefited across the world by raising the standard of living for many, the linear mode of our EEE-WEEE flow is unsustainable (Murthy and Ramakrishna, 2022). Eliminating waste is a major principle of a circular economy (Ellen MacArthur Foundation, n. d.). This study focuses on landfilled WEEE, as landfilling waste is a dead-end stage of a linear economy. The four scenarios analysed in this study, focusing on extension of EEE product lifetime, WEEE collection, reuse of EEE, and material recovery and recycling, are potential contributors to better utilisation of productive resources, a principal goal of a circular economy (Magrini et al., 2020). This study develops a generic system dynamics model for the EEE and WEEE and extend it to eleven WEEE categories in the UK to elicit policy implications. To our knowledge, this is a first attempt to develop a generic SD model and apply it to all categories of WEEE except for three categories for which not sufficient data is available. This approach elicits policy implications in comprehensive and detailed ways. As the results demonstrate there were variations by category regarding the impacts of improvements and required efforts to achieve targeted reductions in landfilled WEEE, implying that policy-makers may focus on certain categories to effectively reduce the total amount of landfilled WEEE.

The sensitivity analyses identify that, while more reuse and more recovery have negligible impacts, households' efforts of longer use of EEE and better WEEE collection were promising. Therefore, further studies to induce households to use EEE longer and cooperate with WEEE collection await (cf. Cole et al., 2019a and b; Król et al., 2016). The backcasting scenario analyses for required efforts to improve WEEE collection reveal that significant efforts are required to reduce targeted amounts of landfilled WEEE.

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CRediT authorship contribution statement

Yoko Nagase: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Data curation. **Takuro Uehara:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All models will be available upon request.

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