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Optimized collection of EoL electronic products for Circular economy: A techno-economic assessment

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Abstract

The relevance of a circular model is widely accepted for the lifecycle management of electrical and electronic products (e-products), given the low recovery rates of valuable resources in current end-of-life (EoL) practices focused on recycling. However, missing insight into the technical and business potential for alternative EoL options (reuse, repair and remanufacturing) holds stakeholders from implementing circular strategies. In this context, our study first mapped by means of material flow analysis (MFA) the life cycle stages of e-products in Denmark and then performed a preliminary economic assessment that evaluates the potential of a circular model. Our findings suggest that a management system centered on reuse could potentially be economically viable, and would likely lead to a substantial cycling of resources and potentially local or regional socio-economic benefits.

1. Introduction

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams globally [1], a fact connected to current linear business models and strategies [2]. These models are characterised by the take-make-waste patterns [3] and are exacerbated by planned obsolescence [4] and the growing global demand for electrical and electronic products (e-products) [5].

In Europe, current formal WEEE management focuses mainly on material recovery [6] but the standardised processing and recycling techniques, which are not equally efficient for all material types, result in material degradation and losses [7]. The new WEEE Directive (recast) [6] and the Circular economy package [8] promise to support a holistic approach for the WEEE management in the future.

In general, circular economy aims to eliminate waste by improved design of products and systems in a way that minimises the use of natural resources and the related environmental impact [2]. Circular models have been widely proposed for the lifecycle management of e-products [9]. Such models prioritise reuse and repair of products over recycling after the first use cycle [10]. However, despite the significant, mostly conceptual, research in this area, there is still a lack of substantial insight and evidence into the technological and business potential for alternative end-of-life (EoL) options based on reuse, repair and remanufacturing. This lack of insight keeps the relevant stakeholders from implementing circular strategies [11].

Barriers for reuse have been extensively discussed and documented [12, 13], but efforts to overcome these barriers are limited today. The four activities that are necessary to implement a circular EoL management system (collection, sorting & testing, recovery and redistribution) are covered by the definition and scope of reverse logistics [14]. Systems based on reverse logistics aim to recapture products at their EoL and thus the residual value (functionality) of whole products or components [15]. Such systems have been mostly studied in the

context of corporate social responsibility (CSR) and extended producer responsibility (EPR) mainly addressing private companies, customers and original equipment manufacturers [15]. Such systems are not integrated into the scope of local authorities, who are responsible for the majority of take-back systems of WEEE. Incentives and strategies developed to facilitate reverse logistics and return of products by the users [16, 17] could also support such broad take-back systems. Previous research pointed at difficulty in forecasting of reverse flows and product quality, and transportation costs that are often higher than in forward distribution, as obstacles to private reverse logistics systems [18]. Other obstacles in reverse logistics networks not only lie at the organization level, but also may be caused by conflicting interests of different stakeholders [19].

In Denmark, the official WEEE collection in 2014 was 12kg/capita [20] or 50% of put on market (PoM) products. However, to meet the new collection target of 65% [6], a better EoL management strategy will be necessary. The relatively efficient formal collection depends largely on citizen satisfaction (environmental consciousness) and convenience [21], and adding economic incentives may have a significant positive influence on the collection rates [16]. Reuse routes, outside the official system, for household equipment are also established in Denmark through resale platforms (e.g. guloggratis.dk), electronic repair shops, refurbish companies (e.g. Bluecity.dk) and charity organisations (e.g. Red Cross) [22]. Further, trading/exchange of items between friends and relatives is not uncommon [23]. However, no study has yet been undertaken to quantify the scale of flows of EoL products through these channels.

The work presented here builds upon previous research at the University of Southern Denmark (SDU). Specifically, a dynamic material flow analysis (MFA) was used to map the flows of PoM products and their corresponding waste in Denmark, based on the existing and projected sales data for the period 1990-2025 [24]. Further, the remaining functionality of EoL products collected through the formal system was thoroughly investigated and showed a high potential for circular economy [11]. The objectives of the present study are: (1) to further map the flows of e-products and WEEE, including unofficial flows, and (2) to perform a preliminary economic assessment that evaluates the potential for a circular model based on optimized collection and preparation for reuse of EoL products.

2. Methodology

We used MFA to map the flows of e-products and WEEE within Denmark [25]. Thereafter, we conceptualised and examined the potential economic viability of a management system that prioritizes reuse.

2.1. MFA of e-products from Danish households

Static MFA was used to map the flows of e-products and WEEE in Denmark for the year 2016. The main flows and methods for their quantification are presented below:

- **PoM products** are officially registered by the Danish Producer Responsibility (DPA) system. Officially, registered amounts show a slow decrease between 2007 and 2013, followed by increase through 2014 and 2015. This increase could partly be attributed to the methodology used for the registration. For example, some common product types addressed both to households and businesses were accounted as household equipment [20]. To correct potential errors, Parajuly et al. (2016) used the primary trade and sales data that focused particularly on household products, including large household appliances (LHA), small household appliances (SHA), consumer equipment (CE) and information technology equipment (ITE) [24]. This accounted for 80% (by weight) of the total PoM products. The data showed that the amounts of PoM remained relatively stable in 2014 and 2015, and would follow a similar trend in coming years. Total household PoM in the present work is based on the latter research, and amounts to 105 kilo tons (kt) (1,000 metric tons (Mt) =1kt).

- **EoL products generated (including WEEE)** follow a similar category and product distribution as the PoM products (minus stock increase). In contrast to this, the WEEE collected though the official system shows significant divergence [24]. This suggests that specific types of e-products might prevalently follow alternative routes at their EoL. The amount of WEEE collected through the official system has been relatively stable at 70kt (2012-2015) [26] and the same amount was projected in 2016. The officially collected WEEE are sent for pre-processing in Denmark or other European countries [20, 27]. The EoL items not collected by the official system inevitably end up in other unofficial routes [24, 28], including items to be prepared for reuse, EoL products disposed in the municipal waste stream (MWS) and sent for incineration [29], as well as documented and undocumented exports either as waste or reusable items [28]. A net stock increase of 2% per year of PoM items in households was accounted for according to the Danish Environmental Agency [28].

- **Flows for direct reuse (unofficial reuse routes)** have not yet been properly quantified and it was not possible to retrieve data directly from some of the platforms that facilitate reuse. Therefore, we empirically assessed the second-hand market of household equipment, specifically flows from user-to-user platforms (i.e. guloggratis.dk) and business-to-user (i.e. Red Cross and bluecity.dk). A repeated sampling was performed by registering all online available items found in the platforms for second-hand products over defined time period and by using the average weight per product type, we estimated the total amount of e-products entering reuse. In order not to overestimate the reuse flow and to avoid double registration of items, guloggratis.dk was taken as the indicative platform for user-to-user trade flow. The sampling covered three months of available and sold items and extrapolated to the yearly flow of second-hand products in Denmark. For business-to-user trades we assessed the reuse flow through Red Cross and Bluecity.dk. We accomplished a few physical visits during which we registered all e-products found in the Red Cross boutiques in the city of Odense. The average amount of e-products found was used to estimate the total flow of reused products in the 329 Red Cross shops across Denmark. Bluecity.dk does not
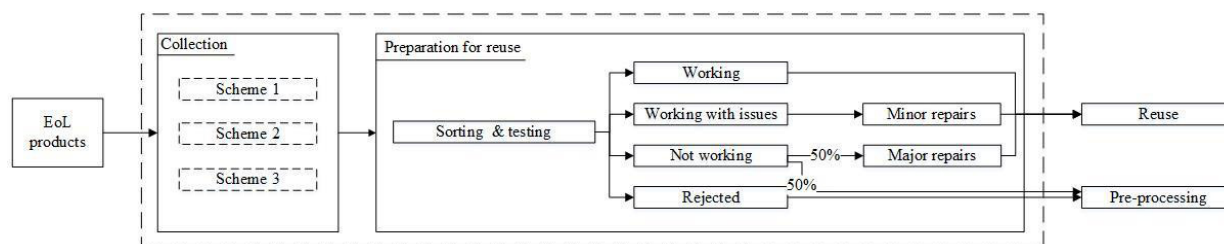
Fig. 1.Conceptual diagram of the proposed management system (dotted square) and the three assessed collection schemes (dashes).

keep hold of sold items, so a precise quantification was not possible without avoiding possible double counting.

2.2. Conceptual model for a reuse-based management system

Fig. 1 illustrates the proposed management system, which has two main components: (1) enhanced collection methods, and (2) facility for pre-sorting and preparation for reuse.

The management system was evaluated as a part of the case study on WEEE collection in Odense municipality. Odense can be considered representative for Denmark regarding household type distribution and population density. The city has 200,000 inhabitants that reside in 53,000 single-family households and 41,000 multi-family households. Housing distribution data and road maps were processed in a geographical information system (GIS) software to calculate WEEE generation potential across the municipality.

The proposed system targets total EoL products generated (with few exceptions). As mentioned in chapter 2.1, total EoL generated have a different product distribution compared to the WEEE collected through the formal system. Since there was no information available on e-products that are not captured by the formal system, and their remaining functionality, we used the product distribution and functionality of collected WEEE as determined by Parajuly & Wenzel [11]. This aspect is discussed in the chapter 3.

The total amount of generated EoL products in Demark is 17.5 kg per capita. Not included were: lighting equipment, medical devices, monitoring and control instruments, as well as automatic dispensers, since they require special treatment and their reuse potential is uncertain. However, these categories consist less than 2% of the total collected amount [20] and the products of these categories are not usually found in municipal collection [11].

2.2.1. Collection schemes

We investigated three collection schemes with closed containers to ensure collection in dry conditions as well as adequate size to handle the disposal of EoL items along with their peripherals. The WEEE generation data across the municipality was used to estimate the expected volume of EoL products for each property. These volumes were used to dimension the three collection systems in terms of number and size of collection materials and collection frequency per year.

Product volumes were calculated using bulk density information, where product categories were grouped in two size fractions, (1) large appliances (LA), including LHA, and (2) small appliances (SA), including SHA, CE, ITE, electrical and electronic tools (EET) and toys, leisure & sport equipment

(TLS). The density of SA (144kg/m^3) was based on the weight and dimensions of the cages that currently accept WEEE in the recycling centres [11] while for LA (183kg/m^3) was based on the average density of ten common large household items [30].

All three schemes are classified as stationary collection systems [30], with containers provided either in municipal collection stations or in housing properties:
- **Scheme 1** assessed the current drop-off collection system with eight recycling centres in the city and the assumed collection rate was 75%.
- **Scheme 2** was used to simulate the existing drop-off collection system used for glass, with 350 spots of collection, with a collection efficiency of 80%.
- **Scheme 3** assessed a system that offers door-to-door collection of EoL products, with a collection efficiency of 90%.

2.2.2. Preparation for reuse

Following the collection, the EoL products are transported to one central facility (in Odense). In this facility, a sorting and testing process takes place and the collected items are first assigned to four functionality categories (% working, % working with issues, % not working and % rejected were assigned according to the category of the WEEE Directive the products belong to [11]). According to their functionality status are then immediately marketed, repaired or sent for treatment. An economic incentive of 10% of the value of remarketed product is given to the owner of the disposed item to further encourage the return of EoL e-products.

2.3. Economic assessment

Potential economic viability was investigated by budget-based economic analysis, which takes into account a total balance of the main financial costs and revenues of a system [31]. The costs analysed in the study included: initial investment, annualized capital expenditure (Capex), operational expenditure (Opex) and potential revenues from the sales of products on the second-hand market and the materials to recycling markets. Potential taxes and subsidies were not included in this study.

2.3.1. Collection costs

Collection costs included: (1) collection materials infrastructure, and (2) collection materials emptying and transport to the central facility.

Capital costs included bins and containers. For scheme 1, LA are disposed in 23m^3 containers (€1,100/container) and SA in 2m^3 containers (€300/container) while the total number of

containers required have the capacity to accept the WEEE generated over the period of a month. For scheme 2, every collection point includes a container for LA (€2,000/container) and a container for SA (€1,000/container). Finally, for scheme 3, single-family properties are provided with one sack (€0.13/sack) every month to dispose of their SA while LA are handled without containers. Multi-family properties are assumed to dispose both LA and SA in box-shaped containers (€2,000/container) that secure the physical condition of the items. Capex was calculated considering an interest rate of 4% and lifetime of the containers of 7 years. Opex included maintenance (5% of the investment) and insurance (0.7%).

Emptying and transportation of materials included the processes of loading, transport and unloading of EoL products with trucks. The cost of collection takes into account operational costs, such as fuel, maintenance and labour [32].

2.3.2. Central facility for preparation for reuse

Investment costs in infrastructure included buildings and equipment. Buildings included: an office area of 30m^2 (€2,069/m^2), a reception hall for loading and unloading of 100m^2 (€1,103/m^2), a storage hall sufficient to store the WEEE collected in three months (€1,103/m^2), and a sorting area of 100m^2, 130m^2 and 150m^2 for scheme 1,2 and 3 respectively (€1,103/m^2). An outside logistic area equal to the total area occupied by buildings (€70/m^2) was added, as well as an unforeseen buildings investment of 20%. The equipment required was accounted as three conveyor belts (€20,000 each), one forklift (€40,000) and unforeseen equipment costs of 50% of the total equipment investment.

Capex was calculated with an interest rate of 4% and lifetime for the buildings of 20 years and 10 years for equipment. Opex included maintenance (3% for buildings and 5% for equipment), insurance (0.7%) and electricity required to operate the equipment (€1/kWh) [31]. Opex also included labour costs which were based on the average working time (1,700 hours/year) and salary in Denmark including: (1) administrative costs (one facility leader (€70/hour), one shift leader (€50/hour), one administration person (€42/hour)) and (2) personnel for sorting and repairs (€42/hour). The latter was calculated according to the amount of e-products received in each collection scheme.

To calculate the amount of labour time needed, the sorting process was divided in four sub-processes: (1) screening, for all the equipment received according to the collection scheme (1 minute/item), (2) quality check, for the assigned working items (10 minutes/item), (3) minor repairs, for the equipment characterised as working with issues (15 minutes/item) and (4) major repairs, for 50% of the equipment assigned as not working (20 minutes/item). Finally, spare parts were assumed to be required only for major repairs and account for the 20% of the value of repaired items.

Revenues for the system were calculated as the sum of the resale value of the products that enter the second-hand market and the value of the WEEE that are sent for recycling. The items characterised as working, working with issues, as well as 50% of the not working items were considered potentially resalable. Therefore, 50% of not working and the rejected items were considered to be sent for treatment. Pre-processing companies pay to acquire WEEE according to the expected material composition per category and the potential material recovery. The average value of recyclable items in the Danish market is €0.3/kg of WEEE [11]. The resale values per functional item, according to the category it belongs (€/kg) were average values estimated for the Danish second-hand market [11].

3. Results & discussion

3.1. MFA results

Fig. 2 shows the flows of e-products and WEEE in Denmark for the year 2016. The amount of PoM products is estimated to be 105kt and is relatively equal to the generated EoL products (103kt), minus the increase in stock [24]. The expected amount of EoL products to be collected through the official system is 70kt while the rest 33kt of EoL products are diverted to other channels. Thus, our estimates show that around 33% of PoM products are collected through complementary routes, compared to the officially reported 17% [28]. These channels consist of e-products exported for reuse outside Denmark (7kt), WEEE disposed through the municipal residual waste (10kt) and presumed undocumented exports (15kt). Out of the 70kt captured by the official system, 50kt are sent for pre-processing in Denmark and 20kt in other European countries.

From the empirical assessment of the second-hand market, we concluded that currently less than 1kt of EoL products are prepared for reuse in Denmark. The flow was for the first time
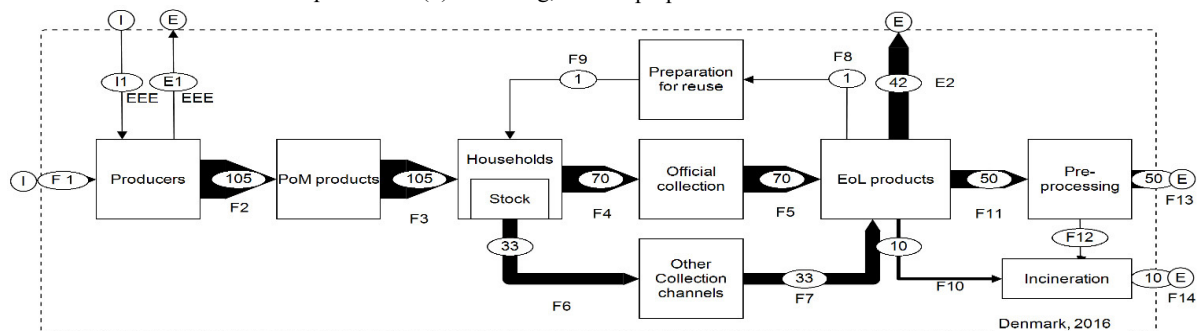

Fig. 2. Quantified flows of e-products and WEEE in Denmark in kt (F1: Input materials, F2: New products, F3: PoM products, F4=F5: Products collected though the official system, F6=F7: Products collected through other routes, F8=F9: Preparation for reuse, F10: Products disposed in MWS, F11: Products sent for pre-processing in Denmark, F12: Residual waste from pre-processing, F13: Recovered materials, F14: Flue gas and combustion residues, I1: Import of new products, E1: Export of new products, E2 : Exports of WEEE and e-products for reuse).

estimated by the DPA system to be 245t for the year 2014 [20]. In this work, we could account for around 600t. Nevertheless, there is a high degree of uncertainty connected to this flow, as it still does not capture all unofficial channels, such as flea markets, thrift shops and other online platforms and direct user-to-user exchanges.

The contribution (by weight) of the sampled platforms guloggratis.dk, Red Cross and Bluecity.dk to the quantified reuse market is 85.8%, 12% and 2.2%, respectively. Nevertheless, the flow through Bluecity.dk could have been underestimated. The sampling shows that the reuse flows mainly consist of high value products. On Bluecity.dk 90% of the available products are ITE, while on guloggratis.dk 55% are ITE and 24% are CE. Red Cross has more uniform distribution within the categories with 33% and 31% of the products to be ITE and CE, respectively. This indicates that the direct reuse today targets high value products, which has an impact on the value of the equipment collected through the official system.

Table 1. Results of the economic assessment in euros (€ - rounded up to three digits), all items are related to 1 year of system operation

Collection	Scheme 1 (€)	Scheme 2 (€)	Scheme 3 (€)
Capex			
- Containers	122,000	205,000	1,559,000
Opex			
- Maintenance	37,000	62,000	442,000
- Insurance	6,000	9,000	62,000
- Emptying and transport	94,0000	231,000	2,516,000
Total	**257,000**	**505,000**	**4,577,987**
Preparation for reuse			
Capex			
- Buildings	62,000	68,000	75,000
- Equipment	19,000	19,000	19,000
Opex			
- Maintenance & Insurance (buildings)	32,000	34,000	38,000
- Maintenance, Insurance & Electricity (equipment)	31,000	31,000	31,000
- Labour	1,600,000	1,688,000	1,864,000
- Spare parts	48,000	51,000	57,000
Incentives	184,000	186,000	209,000
Total	**1,973,000**	**2,074,000**	**2,290,000**
Revenues			
Products for Reuse	-1,838,000	-1,854,000	-2,086,000
Products to Recycling	-414,000	-441,000	-496,000
Total	**-2,251,000**	**-2,295,000**	**-2,582,000**

3.2. Economic assessment results

The results of the economic assessment (presented in Table 1) suggest that the feasibility of the proposed EoL management systems is highly dependent on the applied collection scheme. Revenues balances costs only when the system relies on an improved version of the existing collection at recycling centres (scheme 1). On the other hand, scheme 2 (drop-off cubes) and 3 (door-to-door collection) result in negative economic balances. For scheme 1 and 2, the largest costs are related to the operational costs of the preparation for reuse facility. However, scheme 3 is dominated by costs of collection (door-to-door). Labour costs are important in all three schemes.

The three collection schemes are estimated to incur a total investment in collection materials of €729,000, €1,255,000 and €8,926,000, respectively (without considering the plastics sacks in the door-to-door collection, which are a yearly operational cost). The preparation for reuse facility requires a total capital investment of €841,000, €916,000, €1,008,000, respectively, in the three schemes.

The overall results should be considered preliminary, and require further elaboration before solid conclusions could be drawn. The three systems are dimensioned according to potential generation and reasonable capture rates for EoL products. However, the revenue streams are based on a functionality assessment of WEEE collected in the existing formal WEEE system, meaning that it is most likely underestimated. The costs and revenues calculated, and thus the feasibility of each scheme, are influenced by the capture rate and the quality of EoL e-products. Consequently, further investigation for potential changes in these factors and their impact on the results is required.

The three collection schemes are assumed to be able to capture more EoL products than the existing formal WEEE system. This is largely based on the additional use of economic incentives. The incentives are given to the citizens when their EoL products have been resold. As an example, these transactions can be supported by QR codes, to link each item to its owner, and the amount is credited after the resale occurs. Although small, at 10% of second-hand market value, incentives would probably increase both citizen participation in the collection scheme and the share of functional EoL products.

As indicated by the assessment of reuse channels, direct reuse today targets high value products, which is supported by the fact that products such as laptops and mobile phones rarely enter the official WEEE collection. Thus, an increase in collection is likely to capture more of high value EoL products resulting in an underestimated price per functional unit of each product category in our study. However, capture of the high value products is not expected to change considerably, and is likely to continue to be at least partly outside any formal system, making our approach reasonably realistic.

Moreover, several aspects related to investment and operational costs could be optimized, and require further research. For example, the costs of door-to-door collection, which promises the highest capture rates, could be potentially optimized by offering collection on demand with no permanent collection material infrastructure as recently investigated by Nowakowski et al. [33].

With the proposed system, the rate of preparation for reuse could potentially be increased from less than 1% to 45% (including working and repaired items). Additionally, since sorting, testing and repair are labour intensive activities, this work estimates that the proposed system could create between 22-27 jobs, in the preparation for reuse facility alone.

4. Conclusions

The results of this work indicate that a management system that prioritizes reuse could potentially be economically viable in Denmark, and that the employed collection methods are likely to be the main limiting factor. Major cost burdens are also identified in relation to sorting, testing and repair tasks.

The implementation of such a system could potentially lead to a considerable increase in e-products reuse beyond their first life, and could additionally induce significant socio-economic benefits through job creation.

5. Acknowledgement

6. References

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