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Abstract. In today's highly competitive world, companies need to rethink how they create and capture value at all stages of their offering's lifecycle. A major challenge is to integrate sustainability as a core source of value creation in their business model rather than as an add-on. E-Waste is one of the fastest-growing waste streams globally, and its value is still largely uncaptured. Urban communities generate high environmental and health impacts due to the e-waste produced by households. This paper aims to evaluate the value retained in refrigerators' components at their end-of-life. This research work presents findings on how recyclers identify, categorise, and capture value from e-waste. Although we focus on refrigerators recyclers, the results could motivate refrigerators manufacturers to collaborate with recyclers for a more circular economy.

Keywords: Refrigerators, Circular Economy, Sustainable Business Models, Materials Recycling, Waste Electrical and Electronic Equipment, WEEE, e-Waste.

1 Introduction

Sustainable business model innovation, in the context of the circular economy, looks at how organisations create and capture value at every stage of their offerings' journey to and back from the market [1]. The low-level of integration that organisations have achieved so far between their business models with sustainability is mainly due to treating sustainability as an add-on or a barrier rather than as a new source of value [2], currently being missed, destroyed, or wasted [3]. Many manufacturers miss opportunities to create and capture value while products are in use or even at their end-of-their-life (EOL) when they are recycled or discarded [2,3]. One reason for it is the vision of recycling as the go-to-option and a lack of exploration of value uncaptured from used products [4-6] through other circularity strategies such as remanufacturing [7,8]. A significant example of a case in which value is not always retained is electronic waste (e-waste); one of the fastest-growing streams of global waste. The last decades have shown a worrying increase in the amount of e-waste generated by urban communities; the potential environmental impacts are associated with the toxic chemicals found in most electronic devices. This situation calls for different circularity strategies to collect, sort, and process disposed materials and parts/components for their resale, reuse, repair, refurbish, remanufacture, repurpose, and recycling [7,8].

Environmental Regulation Agencies have insisted that attention must be paid when dealing with Waste Electrical and Electronic Equipment (WEEE) because they contain toxic materials (e.g., heavy metals, polybrominated diphenyl ethers, phthalates, and polyvinyl chloride). If managed improperly, the disposal of WEEE can adversely affect the environment and human health [9]. Some examples of large household products that are categorised as e-waste are refrigerators, freezers, electric stoves, microwaves, washing machines, dryers, air conditioners, to mention a few.

The production of large quantities of e-waste is a consequence of increased global consumption of electronic products and an outcome to technological products obsolescence caused by fast-paced new technology developments [10]. Refrigerators are one of the products that fall under the definition of e-waste, meaning that their treatment must follow the WEEE regulations from the European Union [11]. Some companies have found and created a business case out of the management of the EOL of these electrical and electronic products. However, current documented solutions are limited to the recycling of refrigerator components, disregarding other possible circular solutions. Part of this challenge relates to the founding of business cases, which has been limited because the economic viability of material recycling requires high volumes that are not be always reachable at trial-stages of a business case. Additionally, there is a high level of complexity caused by uncertainty and lack of data within supply chains, which relates to the quantity, quality, and timing of inputs for circular processes [12]. Particularly in e-waste treatment, recyclers have very limited visibility of the amount and state of the EOL products that they will receive in their facilities, which limits their planning capabilities and the possibility of innovative thinking.

The purpose of this research work is to identify and understand which are the disposed materials and parts/components of refrigerators that retain the most value at the EOL. This could provide recycling companies with a better understanding of how they could prioritise material handling, which leads to innovations in their production line. Although these efforts have an impact mainly in the part of the supply chain that handles EOL products, it is expected that the understanding of value both in material and data could help close-the-loop back to refrigerator manufacturers in a circular supply chain [13].

2 Research Question and Method

The research question is *how to identify and understand which are the disposed materials and parts/components of refrigerators that retain the most value at the EOL?* The research method followed is a *state-of-the-art literature review* [14] about e-waste, business models, and Circular Economy. The purpose of this literature review is to identify (new) sources of value at EOL of refrigerators, and other home appliances, which allow the authors to extend their search opportunities while creating generalisation statements on how to prioritise material handling to maximise value capture.

To begin the literature review, the authors explored the following search string in Scopus: *(TITLE-ABS-KEY ("refrigerator" OR "home appliances") AND TITLE-ABS-KEY ("recycling" OR "end-of-life") AND TITLE-ABS-KEY ("spare parts" OR "materials"))*

The search in Scopus gave place to 163 documents. After screening the abstracts, the authors selected 85 papers that showed a contribution to answering the stated research question, meaning that they referred to material value at the EOL of electronic appliances or explicitly techniques and technologies for recycling. However, from this selection, only 68 records where found online, mainly because the other 17 belonged to conference proceedings that were not public, or with the full text translated to English.

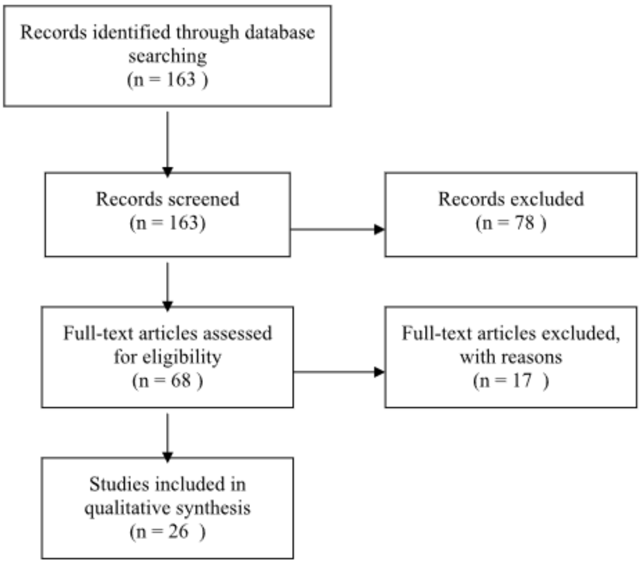

Fig. 1. PRISMA Diagram of Literature Review Process

3 Literature Review

The process of categorizing the literature review findings started with two main categories, which were previously specified in the research question, valuable materials and recycling techniques. However, the articles included an extensive amount of methods used for assessment of the process and innovative proposals for value generation, which led the authors to create two additional categories that reflected the value of previous contributions. Finally, the findings from the literature review are grouped into four categories for further scrutinization: (i) methods for the analysis of recycling process, (ii) techniques in the recycling process, (iii) materials categorised as valuable, and (iv) innovative proposals for value generation.

3.1 Methods for Analysis of the Recycling Process

The use of *dynamic flow analysis*, which can estimate a product lifecycle length, can help to calculate the state of metals and plastics contained in obsolete refrigerators [15]. Also, the application of IoT has been explored in refrigerators, where through sensors, Bluetooth, and RFID technology there is the potential to provide visibility of maintenance requirements and make life-length estimations [16].
This proposition can be useful to face one of the main challenges identified in EOL management organisations such as remanufacturers and recyclers; the high levels of uncertainty on the input of circular process, given that the demand or input of the circular process/system is difficult to predict.

Also, authors in [17] and [18] make use of material flow analysis and Life Cycle Assessment (LCA) in China to compare different EOL strategies for e-waste. This type of information can enable countries and regulation organisations to have better understandings of how to support organisations in their road to improved operations that allow positive sustainability implications.

3.2 Techniques in the Recycling Process

Some papers explain that organisations usually incorporate manual dismantling in the treatment of e-waste as it leads to higher efficiency [19]. However, this step is usually manually intensive and possibly one of the higher-risk activities during recycling because there is a lack of planning at the design-stage that supports disassembly, such as modular design. This means that the process combines operations where major components such as compressors, interior shelves, and storage bins are removed manually with mechanical operations such as shredding and automatic physic sorting (see [17], [20], and [21]). In [20] it is suggested that the potential resells for refurbishment is analysed through an evaluation that precedes the complete disassembly of refrigerators. This statement is particularly remarked for the evaluation of compressors, which through a filter could assess its technical performances such as the input power [22].

Additionally, enclosed and depressurised environments are proposed to avoid the dispersion of hazardous components such as refrigerants contained in the polyurethane foam of refrigerators [21]. The proper evacuation of the refrigeration circuit shall be ensured by monitoring devices that adapted to the extraction system; appliance volume appliance shall be integrated into the extraction system [23].

3.3 Materials Categorised as Valuable

In [15], [17], and [24], the materials highlighted are precious metals (Au, Ag), common Metals (i.e., Fe, Al, Cu, Sn), and toxic metals (i.e., Pb, Sb, Cd, Hg). However, the main environmental benefits are due to the recycling of steel, aluminium and copper [17].

After resource recovery, valuable resources such as copper, scrap, metal, and plastics are sold or exported to recycling companies, and low-value residues such as oils, waste refrigerant, and urethane are disposed to landfills or incinerated. The authors state that with a more active recycling of urethane, it will be possible to recycle most of the resources from waste refrigerators collected by both the formal and informal sectors [25].

To avoid the degradation of the quality of copper produced, all materials are processed to make copper cathode because no brass or wire will be produced in this recycling process. Magnetic separation is proposed to remove steel from scrap. Then non-ferrous metals and plastics shall be treated by air separation. Finally, light metals such as Aluminum and heavy metals such as copper are separated by density separation [26].

Regarding plastics, the material used is mainly polystyrene, which represents a high value in terms of the market prices for this secondary raw material. The techniques for separation are usual ones like swim sink separation and hydro cyclone classifier [23].

Fig. 2. Recyclable Materials and Parts of a Refrigerator

3.4 Innovative Proposals for Value Generation

The recycling of materials could be critical for countries with high metal demand, such as China and Japan. In China, only 40% is met by domestic deposits, and in Japan [26] new strategies are being developed to look ad deep ocean mining to avoid importing metals. Therefore, the efficient recycling of refrigerators and other types of e-waste could be highly beneficial to help cover this demand [27].

An innovative strategy is proposed in [28], where the use of fibber extracted from refrigerator door panels (FERD) and waste plastic in bituminous mixes for road construction. Also, [29] suggests diverse applications that generate insulation materials of EOL refrigerators. For example, due to their versatility, polyurethane (PU) foams have many different applications, such as sponges, filling materials in furniture, automotive seats and clothes, among others.

For strategies that include upcycling or finding higher value in an EOL product than just the recycling of the material components, this process would require examination of the end-of-life product to try and choose an activity that goes higher in the waste pyramid, through reuse or refurbishment [24]. However, a rigorous and fair comparison of EOL handling options for domestic refrigerators is much more complicated than simple policy perspectives such as the waste hierarchy might suggest [17], [30].

4 Conclusions & Outlook

This paper focused on contributing to a better understanding of the emerging circular business opportunities for the refrigerators manufacturers and recyclers, particularly those circularity opportunities at the middle-of-life (MOL) and EOL of refrigerators.

Circularity strategies present a wide range of strategies ordered from high-level strategies like resale, reuse, repair, refurbish, and remanufacture to low-level strategies such as repurpose (e.g., parts cannibalization) and recycling based on their resource-conservation capabilities (e.g. materials and energy) [7,8]. Thus, refrigerators manufacturers and recyclers should aim to move their environmental efforts to higher levels of circularity by redesigning their offerings for ease of maintenance and repair, upgradability and adaptability, and disassembly and reassembly to servitise them for longer lifecycles (i.e., product lifecycle extensions) [31]. A future research perspective is to look at the example of refrigerators and freezers that are already included in rentals of flats and houses, where [32] suggests that the constant contact of landlords with service and use contracts motivates manufacture to design for easier repair and refurbishment.

Achieving more sustainable solutions is an undiscussable priority, considering that the availability of refrigerators and freezers in any household is unavoidable. The mentioned solutions require compromise and communication between suppliers, manufacturers, distributors, users and EOL treatment plants to better understand the prioritisation of value for each stakeholder and together find sustainable value.

Through strengthened supply chains that have visibility along the entire lifecycle of a product, we could foresee in a future scenario where recycling is not the first choice for e-waste treatment. Recycling could one of the last options to recover the value of materials, parts and components so that virgin material extraction is reduced and therefore the environmental impact of resources extraction can be decreased.

Future research in terms of material value requires more exploration of how to create business cases out of small material fractions to make use of the polymers retrieved in refrigerators. Also, the use of alternative materials which lead to components that can be designed for more circular strategies could support a more sustainable future.

Finally, higher-level circularity strategies will offer not only a better environmental performance to the refrigerator manufacturers and recyclers, but also new revenue streams based on MOL and EOL services as they start exploring the vision of circular refrigerators.

References

1. Geissdoerfer, M., Vladimirova, D., Evans, S.: Sustainable Business Model Innovation: A Review. Journal of Cleaner Production, Vol. 198, pp. 401-416 (2018)
2. Yang, M., Vladimirova, D., Evans, S.: Creating and Capturing Value Through Sustainability. Research-Technology Management, 60(3):30-39 (2017)
3. Bocken, N., Short, S., Rana, P, Evans, S.: A Value Mapping Tool for Sustainable Business Modelling. Corporate Governance, 13(5):482-497 (2013)
4. Yoon, H., Jang, Y.C.: The Practice and Challenges of Electronic Waste Recycling in Korea with Emphasis on Extended Producer Responsibility (EPR). IEEE International Symposium on Electronics and the Environment, pp. 326-330 (2006)
5. Lee, S.J., Cooper, J., Hicks, G.: Characterization of Monitor Recycling in Seattle, Washington. Regional Environmental Change 10(4):349-369 (201)
6. Tong, X., Tao, D., Lifset, R.: Varieties of Business Models for Post-Consumer Recycling in China. Journal of Cleaner Production, Vol. 170, pp. 665-673 (2018)
7. Thierry, M., Salomon, M., Numen, J. V., Van Cazenove, L.: Strategic Issues in Product Recovery Management. California Management Review, 37(2), pp. 114-135 (1995)
8. Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A.: Circular Economy: Measuring Innovation in the Product Chain. Policy Report. The Hague: PBL Netherlands Environmental Assessment Agency (2017)
9. Jang, Y.C.: Waste Electrical and Electronic Equipment (WEEE) Management in Korea: Generation, Collection, and Recycling Systems. Journal of Material Cycles and Waste Management, 12(4):283-294 (2010)
10. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H.: Global Perspectives on e-Waste. Environmental Impact Assessment Review, 25(5):436-458 (2005)
11. European Parliament: L197/38 – WEEE Directive (Recast) 2012/19/EU. Official Journal, European Union, June, pp. 38-71 (2012)
12. Bressanelli, G., Perona, M., Saccani, N.: Challenges in Supply Chain Redesign for the Circular Economy: A Literature Review and a Multiple Case Study. International Journal of Production Research, 57(23):7395-7422 (2019)
13. Romero, D., Molina, A.: Reverse - Green Virtual Enterprises and their Breeding Environments: Closed-Loop Networks. IFIP, AICT, Vol. 408, pp. 589-598 (2013)
14. Grant, M.J., Booth, A.: A Typology of Reviews: An Analysis of 14 Review Types and Associated Methodologies. Health Information and Libraries Journal, Vol. 26 pp. 91-108 (2009)
15. Li, X., Ren, Q., You, X., Yang, Y., Shan, M., Wang, M.: Material Flow Analysis of Discarded Refrigerators from Households in Urban and Rural Areas of China. Resources, Conservation and Recycling, Vol. 149, pp. 577-585 (2019)
16. Fiore, S., Ibanescu, D., Teodosiu, C., Ronco, A.: Improving Waste Electric and Electronic Equipment Management at Full-Scale by Using Material Flow Analysis and Life Cycle Assessment. Science of The Total Environment, Vol. 659, pp. 928-939 (2019)
17. Osisanwo, F., Kuyoro, S., Awolede, O.: Internet Refrigerator – A Typical Internet of Things (IoT). 3rd International Conference on Advances in Engineering Sciences & Applied Mathematics, pp. 59-63 (2015)
18. Lu, B., Song, X., Yang, J., Yang, D.: Comparison on End-of-Life Strategies of WEEE in China based on LCA. Frontier of Environmental Science & Engineering, 11(5) (2017)
19. Umeda, Y., Miyaji, N., Shiraishi, Y., Fukushige, S.: Proposal of a Design Method for Semidestructive Disassembly with Split Lines. CIRP Annals - Manufacturing Technology, 64(1):29-32 (2015)

20. Kim, K., Cho, H., Jeong, J., Kim, S.: Size, Shape, Composition and Separation Analysis of Products from Waste Refrigerator Recycling Plants in South Korea. Materials Transaction, 55(1):198-206 (2014)
21. Ruan, J., Qian, Y., Xu, Z.: Environment-friendly Technology for Recovering Nonferrous Metals from e-Waste: Eddy Current Separation. Resources, Conservation and Recycling, Vol. 87, pp. 109-116 (2014)
22. Ng, Y.T., Lu, W.F., Song, B.: Improving Green Product Design with Closed-Loop Product Recovery Information. Key Engineering Material, 572(1):12-15 (2014)
23. Keri, C.: Recycling Cooling and Freezing Appliances. Waste Electrical and Electronic Equipment Handbook, pp. 339-351 (2012)
24. Nguyen, D.Q., Ha, V.H., Eiji, Y., Huynh, T.H.: Material Flows from Electronic Waste: Understanding the Shortages for Extended Producer Responsibility Implementation in Vietnam. Procedia CIRP, Vol. 61, pp. 651-656 (2017)
25. Yi, S., Lee, H., Lee, J., Kim, W.: Upcycling Strategies for Waste Electronic and Electrical Equipment based on Material Flow Analysis. Environmental Engineering Research, 24(1):74-81 (2019)
26. Motoori, R., McLellan, B.C., Tezuka, T.: Environmental Implications of Resource Security Strategies for Critical Minerals: A Case Study of Copper in Japan. Minerals, 8(12):558 (2018)
27. Wang, J., Ju, Y., Wang, M., Li, X.: Scenario Analysis of the Recycled Copper Supply in China considering the Recycling Efficiency Rate and Waste Import Regulations. Resources, Conservation and Recycling, Vol. 146, pp. 580-589 (2019)
28. Baxter, J.: Systematic Environmental Assessment of End-of-Life Pathways for Domestic Refrigerators. Journal of Cleaner Production, Vol. 208, pp. 612-620 (2019)
29. Dos Santos, L.M., Carone, C.L.P., Dullius, J., Ligabue, R., Einloft, S.: Using Different Catalysts in the Chemical Recycling of Waste from Flexible Polyurethane Foams. Polimeros, 23(5):608-613 (2013)
30. Ranadive, M.S., Hadole, H.P., Padamwar, S.V.: Performance of Stone Matrix Asphalt and Asphaltic Concrete using Modifiers. Journal of Materials in Civil Engineering, 30(1):1-9 (2018)
31. Bakker, C., Wang, F., Huisman, J., den Hollander, M.: Products that Go Round: Exploring Product Life Extension through Design. Journal of Cleaner Production, Vol. 69, pp. 10-16 (2014)
32. Fiore, E.: New Strategies for the Refrigerator in the Transition Towards a Circular Economy. Proceedings of Relating Systems Thinking and Design 7 (RSD7), pp. 134-148 (2018)