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CIRCULARITY OF PLASTICS THROUGH ECODESIGN: THE CASE OF FRENCH WEEE

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ABSTRACT

While innovation in waste treatment processes continue to advance, plastics are still often put aside in comparison to other materials. It is especially the case for WEEE-plastics: as they are included in complex equipment, their recovery is disregarded, in aid of critical metals and rare earths. The recycling of plastics is hindered by the low re-integration rate of these materials, due to concerns around their quality and their availability. Ecodesign of EEE thus seems to be a robust solution. This paper details two approaches to assess product design, by respectively evaluating the product recyclability and the implementation of predefined ecodesign guidelines. Based on these methods, the construction of a quality standard for recycled plastics in France is presented. The definition of the quality includes mechanical properties, but chemical, logistics, and regulatory aspects are also at stake. Eventually, ecodesign indexes and indicators are selected, and a method for their formal construction is proposed. The goal of this study is to provide ways to assess the overall quality and usability of recycled plastics, along with design for circularity methods to integrate them in new manufactured products.

Keywords: Circular economy, Ecodesign, Sustainability, WEEE, Plastics

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1 INTRODUCTION

1.1 Industrial context

Treating waste aims at reducing the global environmental impact of a product, while recovering some of its economic and material value (Gaines, 2012). Therefore, the development of these treatment processes is often discussed in scientific literature. When evaluating the environmental efficiency of existing end-of-life (EoL) treatment options, a hierarchy can be made. The best option is to prevent of the generation of waste, with lifespan extension processes such as maintenance, or preparation for reuse. Then, material recovery by recycling, and energy recovery through incineration can be considered. The least preferred option is to dispose of the waste, by incinerating it without energy recovery or landfilling (Andersen, 2021; Dwek, 2017).

More specifically, the improvement of the recovery rate of materials and products is a dominant issue. This rate can be related to either functional, material or energy recovery options, and is respectively called reuse rate, recycling rate and energy recovery rate. They are calculated by stakeholders of the recycling chains, and are based on real data obtained from the measured efficiency of the processes (Grimaud, 2019). Moreover, it is also possible to improve the environmental characteristics of a product during the design stage. This design for end-of-life, or ecodesign, aims at predicting the behaviour of disposed products that are sent to be treated by one of the possible options (Dostatni et al., 2016). A taxonomy and glossary of ecodesign and circular economy has been made by De los Rios and Charnley (2017).

In Europe, ecodesign is the direct consequence of European legislations, that set objectives for the recovery of waste electrical and electronic equipment (WEEE). Member states must reach these objectives, and shall implement policies based on common ISO norms and standards (Rodriguez Moreno, 2016). In France for instance, producers of electrical and electronic equipment (EEE) can delegate the responsibility of collection and treatment to the producer responsibility organisation (PRO) *ecosystem*, which oversees household and professional WEEE (Code de l'environnement, 2017).

The PRO *ecosystem* seeks new methods to improve the communication between plastics recyclers and recycled plastics users. In most cases the design teams are unaware of the current state of the available treatment technologies, and are unable to predict correctly where and how their product will be recycled (Martinez-Leal, 2019). This issue is even more relevant for EEE as they are composed of numerous materials, such as metals, rare earths, glass and plastics, which often arrive mixed altogether in the recycling chains. Hence, their recycling is difficult, and most of the non-metal materials are not recovered (Horta Arduin, 2020). In the case of *ecosystem* and their search for a common communication tool for recyclers and EEE producers, a research and training Chair has been created, in partnership with several engineering schools (ENSAM, Chimie ParisTech, Mines ParisTech).

The present study is the result of this partnership. Its goal was to build a document that serves as a common reference for plastics recyclers and EEE producers. Hence, the construction of a quality standard for recycled plastic materials (RPM) was decided in order to convey satisfying data on the characteristics of a recycled plastic, while respecting the balance between what can be provided by the plastics recyclers, and the data requirements from the producers of plastics and EEE products. With this approach, we hope that the RPM quality standard will promote the use of recycled plastics, by presenting them as real alternatives, and not as subpar materials that cannot meet product specifications.

1.2 Indicators for the recycling chain

To make ecodesign relevant, EoL treatment options must be evaluated, and the results transmitted to the design teams. To this end, key performance indicators (KPI) can be used as a communication tool.

First, the perimeter of each process within the treatment chain must be defined. We can consider a generic chain of processes used for WEEE (Buekens and Yang, 2014). Such a chain is presented in Figure 1. The mass of waste entering each process or group of processes is also represented.

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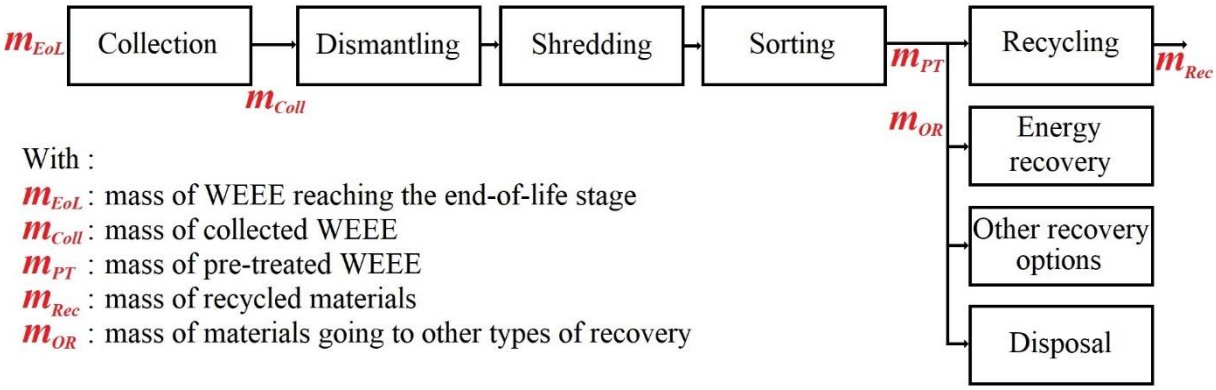

Figure 1. Perimeter of the waste treatment chain

Each process has its own efficiency rate, hence, several KPIs can be defined (EU Parliament, 2011; Martinez-Leal, 2019):

$$R_C = \frac{m_{Coll}}{m_{EoL}} \quad (1)$$

$$R_{REoL} = \frac{m_{Rec}}{m_{EoL}} \quad (2)$$

$$R_{RC} = \frac{m_{Rec}}{m_{Coll}} \quad (3)$$

$$R_{ER} = \frac{m_{Rec}}{m_{PT}} \quad (4)$$

$$R_R = \frac{m_{Rec}+m_{OR}}{m_{EoL}} \quad (5)$$

with:

R_C : the collection rate of waste;
R_{REoL} : the total recycling rate of all end-of-life waste;
R_{RC} : the recycling rate for collected waste;
R_{ER} : the efficiency of the recycling process;
R_R : the recovery rate.

Thus, the recovery rate is the mass ratio of all waste that are either functionally, materially, or energetically recovered. The current key performance indicators only focus on the mass of treated material, and not on other important aspects such as the circularity and quality of the latter. This created huge discrepancies in the recycling rate of different materials.
For instance, plastics contained in WEEE are almost never recycled, as shown in Table 1 (Fangeat et al., 2020; Horta et al., 2019; Plastics Europe, 2020).

Table 1. Recycling and recovery rates of plastics from WEEE

	WEEE Small IT and telecom	Plastic fraction in WEEE
R_C	53%	
Proportion of plastics	31%	78%
R_{ER}	87%	53%
R_R	85,2%	55%
R_{REoL}	41,6%	11%

The typical way to retrieve plastics from the WEEE waste stream is to sort them from the ferrous and non-ferrous metals (Ragaert et al., 2017). In the end, a mix of plastic fragments is obtained, that is called the plastic fraction. Here we can observe that the proportion of plastics within the plastic fraction is only 78%. This means that 22% of the total mass of this fraction is composed of contaminants that will negatively impact the recycling process of WEEE-plastics (Horta et al., 2019). Public instances often communicate the recovery rate of WEEE, but as we can see, it is important to decompose this rate to see which materials are recycled, and which ones are sent to energy recovery.

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Another issue regarding the plastics from WEEE that are actually recycled is their low circularity, indeed less than 3% of these were re-integrated in the manufacturing of new equipment in 2019 (Plastics Europe, 2020). According to the same study, most of these plastics were sent to low-quality applications, such as agriculture or building. Plastics can for instance be used for agricultural tarpaulins, or in the filling of concrete blocks (Kaliyavaradhan et al., 2022).
Moreover, a survey among European plastics users revealed that only 53% of them were inclined to buy recycled plastic materials (RPMs), most of them justifying their choice by the unstable quality of RPMs, the insufficient volume available to purchase, and more generally, the lack of available information on these materials (EuPC and PCE, 2019). More specifically, 74% of respondents voiced concerns about the quality of the recycled plastics, and 39% complained about the lack of supply.
To answer all these issues, we must propose new ways to communicate data on the properties and availability of recycled plastics. Besides, the evaluation of waste treatment efficiency is inadequate, as it focuses only on the mass of retrieved materials, but ignores other circularity aspects. To this end, new indexes for material circularity must be created.

2 METHODS FOR ECODESIGN

2.1 Existing methods to evaluate product ecodesign

As previously shown, the recovery rate is a practical calculation, based on real figures. However, during the product design stage, the design teams can only try to predict the potential recovery rate of the product. To do so, the recoverability rate is evaluated. For EEE, it is defined in European legislation as such (AFNOR, 2012; CEN/CLC/TC, 2019):

$$R_{Rec} = \frac{\sum_{i}^{n} m_{i} * R_{RTh_i}}{m_{EEE}} \tag{6}$$

With:

R_{Rec} : recoverability rate of the equipment;
m_i : mass of the ith component;
R_{RTh_i}: theoretical recovery rate of component *i* in the predicted end-of-life treatment option;
m_t : total mass of the equipment.

The recoverability rate is a theoretical calculation, based on scenarios created by the product design teams. Once again, we can observe that this is a mass rate, and that it will favour heavy materials such as metals over lighter ones, such as plastics.
Therefore, specific methods have been created, which take into account real data from treatment plants. An approach based on the life cycle analysis of European plastics has been implemented by Schwarz et al. (2021), that aimed at finding which treatment method is the most environmentally efficient. The study was conducted on the 15 most used plastic types in Europe, and showed that the best treatment method differs for each polymer type.
Indeed, the recoverability of a material is also tightly linked to its integration into a product. The overall design of an equipment will greatly influence its ability to be dismantled and the ability to sort its constitutive materials. For EEE, the notion of complex products apply; it refers to the fact that they contain numerous materials that are linked in a way that does not allow for a simple dismantling, which often implies that the materials cannot be separated during the sorting process (Grimaud, 2019).
Thus, evaluating the level of design for end-of-life of products is a complex process, but it is necessary to thoroughly assess the environmental impact of a product. Some authors have created methods to fulfil this task.
On one hand, it is possible to individually evaluate each aspect of the eco-design. For instance, De Aguiar et al. (2017) have created a tool to evaluate the recyclability of a product during the design phase.
The indicators they have selected can be separated into three categories:

- Indicators for the recycling chain;
- Indicators for the product;
- Indicators for the materials.

Each of these categories has a specific perimeter, which allows for the analysis of the product's strengths and weaknesses, along with the origins of the latter. In this case, the materials constituting the product, its design, or its integration into treatment chains are three potential points of improvement.

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On the other hand, global approaches that focus directly on the ecodesign guidelines can be used. Peters et al. (2012) have created a practical tool that evaluates the recyclability of small WEEE. The approach was quite different, as they did not separate the impacts, rather the recyclability is directly evaluated by the tool: a datasheet lists a variety of ecodesign guidelines, and for each of them the user must specify for each product if it is implemented by the company. According to the number of guidelines followed, the tool was able to give a recyclability index. Each guideline was weighted, according to its importance. The weights were found by carrying out surveys among project partner engineers.
Hultgren, (2012) commented on this method, stating it was of interest for the engineers, but that it was not used in practice, because 57% of the guidelines represented 15% of the total recyclability score. Indeed, the tool was supposed to give clear recommendations, and a Pareto distribution would have been less confusing for the users.

2.2 Building ecodesign indicators

Based on the studies previously mentioned, we have written criteria that we believe ecodesign tools should respect.
First of all, the design teams will be able to use this tool only if it allows for a quantitative analysis of the viability of use of the materials. This means that the chosen indexes and indicators must be comparable to design criteria such as the costs, the availability of the supply, the processability of the materials and the mechanical specifications of the final product.
For the same reasons, multi-criteria analyses are more efficient, and should, if possible, include technical, material, economic and environmental aspects.
The indexes must also take into account the complexity of the products, especially high in the field of EEE. This also includes the reality of the WEEE treatment: all steps of the treatment chain must be acknowledged.
Eventually, the whole design of the product must be included in the perimeter of the indexes, that is to say, the end-of-life behaviour of the product, but also its global architecture. For EEE, the latter refers to the modularity or dismantlability of the product and components.
In order to give ecodesign guidelines for EEE, indicators and indexes have to be built, as they represent an efficient communication tool for product designers. Following the approach presented in Section **2.2**, it was decided to build a *recoverability index*. It includes the global design of the product through the dismantlability and the separability of the materials, and it also promotes the choice of a recoverable material.
Moreover, as previously presented, the re-integration of recycled plastics into new EEE is also lacking. Hence, a *re-integrability* index also had to be built. Following the criteria previously presented, we build this index around three indicators, presented in Table 2. This index takes into account the supply availability of the material, its chemical composition and its traceability.
Table 2 gives the detailed definition of these two indexes.

Table 2. Selected ecodesign indexes and indicators

Recoverability index		**Re-integrability index**	
Indicators	Measurable values	Indicators	Measurable values
Dismantling potential	Number of fasteners Accessibility of the part Number of fastener types Type of fastener	Material availability	Volume of the deposit Supplier's production capacity
Material separability	Quantity of materials Material compatibility Hazardous materials Material contamination	Material purity rate	Polymeric contaminants Other contaminants Proportion of minerals Maximum size of contaminants
Material recoverability	Material reuse rate Material recycling rate Material energy recovery rate	Material traceability	Industrial sector of origin Geographic origin Waste pre-treatment processes Waste regeneration processes Regulation compliance

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The recoverability index evaluates the capacity of a material to be retrieved from the final product, whereas the re-integrability index is a material circularity index. It expresses the capacity of a recycled material to be used once again in an industrial application.
The calculation of the re-integrability index indicator is directly based on measurable values obtained from the RPM quality standard, that will be presented in Section 3.

3 RESULTS

3.1 A datasheet for recycled plastics: the case of French WEEE-plastics

It was decided to build a first version of the RPM quality standard, that would be easily usable at an industrial level, and would rank up the properties necessary to evaluate the quality of a recycled plastic batch. This first version took the form of a technical datasheet for RPMs. This document being a communication tool between protagonists from the sector of recycled plastics, the first objective was to find a consensus on its content.
After analysing the methods mentioned in the previous section, it was decided to include the industrial partners in the discussion. A first version of the datasheet was proposed, which listed very common chemical and mechanical properties. The first list of properties included in those categories was drawn by analysing the existing norms on plastics recycling in Europe.
Besides, following the approach of Peters et al. (2012), each property was weighted, in order to take into account the overall relevance of each one. Then, properties were added or discarded according to their importance and relevance to EEE producers and plastic recyclers.
To evaluate this first version, a thorough survey was sent to six volunteering industrial partners. They were interrogated on four criteria (each including several sub-questions): the ergonomic design of the datasheet, the properties listed in the sheet, the associated norms and standards, and the overall usefulness and relevance of the datasheet. This approach helped us identify which properties were missing, which ones were more or less important, and which norms were in use in the industry. Besides, it also helped us gauge how the use of a common framework would impact the work of plastic recyclers and EEE producers.
In addition, a formal workshop was set up by *ecosystem*. During this meeting, through their network of industrial stakeholders, engineers from 10 recycling companies and 15 EEE manufacturing companies were interviewed. They were able to help us rank the properties, in order to give them their first weighting. Moreover, this workshop also led us to the current format of the datasheet, a fillable document with properties classified into specific categories. This workshop was also an occasion to present our work to official organisations such as the *FEDEREC*, the French professional federation of recycling companies.
Several other less formal meetings took place, so that the industrial stakeholders could voice their potential concerns or suggest some improvements. After this design process, it was clear that the quality of a recycled plastic did not only come from mechanical properties. The RPM technical sheets had to include every criterion that made the plastic usable in an industrial application. Eventually, eight categories were singled out: chemical composition, mechanical and functional properties, processability of the plastic, regulation compliance, quality insurance, supply and storage, traceability of the waste, and environmental impact.
The technical sheet is typically filled in by the recycler. By doing so, the sheet displays an index, that is a direct function of the number of properties that have been filled in. Indeed, it is difficult to grade the material quality of a recycled plastic batch, as it will depend on the application the EEE producer has planned for it. However, a high index will mean that the recycler has given enough information for the users to decide if the plastic batch meets their needs or not. The goal of the weighting is thus to highlight the recycler's efforts in filling in the most important data. Indeed, we have found that small businesses might not have the financial capacity to test for every property listed in the sheet, that is also why a weighting has been put in place: filling out all the most essential properties, that every EEE producer needs to know, ensures a relatively high index. In total, the datasheet was built over the course of sixteen months.
For an optimal versatility of the tool, three versions of the sheet have been designed (Nève, 2022):

- A *complete* version, containing all the parameters, which is intended to be filled in as much as possible by the recycling company;

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- A *generic* version, which includes a reduced list of the parameters deemed most important and proposes a printable visual rendering of the form. The blank model is made available to recyclers, which provides them with a tool for establishing an initial exchange with users. A recycler could fill it in for several of his plastics and thus establish a sort of catalogue of their possibilities;
- An *exchangeable* version, which includes all the parameters, as well as a "User Requested" column that allows the user to specify their expectations. Answering "No" reduces the parameter's weighting coefficient to 0. This model of sheet is designed to go back and forth between the user and the recycler several times, and as the exchanges progress, the parameters that are interesting to the user would be filled in, and the others would disappear. This version could be used in design, during material selection, to ensure whether a batch is usable for the intended application.

These datasheets are meant to be usable in an industrial context, and have been designed to be relevant to both the recycled plastic providers and the EEE producers. Thus, we now need a common document that can be used as a reference for the measurement of each of the selected properties.

3.2 Towards a common reference for the quality of recycled plastics

The structure of the RPM quality standard is based on the work carried out with *ecosystem*. Each property listed in the sheets has been compared with existing norms and standards, and those mentioned in these standards have been retained.

However, as opposed the technical sheets, it is not a weighted, rather it is an objective and thorough list of properties. For each of the latter, the document provides the user with existing measurement methods, norms and standards.

The RPM quality standard has been directly tested by two recycling companies: the French recycling company *Skytech*, and the Dutch recycling company *COOLREC*, who filled in the document for one of their products. Their contribution allowed us to adjust the contents of the standard, in terms of listed properties and associated norms.

The nine final categories, along with the most important properties within each one are given here below:

- Chemical properties
  - Main resin
  - Polymeric impurities
  - Fillers, stabilizers and intentionally added substances (IAS)
- Mechanical properties
  - Impact strength
  - Bending modulus
  - Tension modulus
  - Density
- Functional properties
  - Colour and external aspect
  - Moulding shrinkage
  - Certification for household WEEE
- Thermal properties
  - Melt flow index
  - Vicat softening temperature
  - Fire resistance certification
- Material traceability
  - Waste stream of origin
  - History of use (post-industrial / post-consumer)
  - Pre-treatment processes
  - Post-sorting regeneration processes
- Regulatory compliance
  - Reach compliance (IAS and non-IAS)
  - RoHS compliance (IAS and non-IAS)
  - POP compliance (IAS and non-IAS)

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- Quality management
  - Available additional documentation on the batch
  - ISO 9001 certification
- Logistics
  - Batch size and storage conditions
  - Estimated volume of the deposit
  - Volume available to purchase
  - Possibility of a volume-based contract
- Environmental footprint
  - Share of recycled materials in the batch
  - Carbon savings
  - Type II and III environmental declarations

In total, the RPM quality standard contains 62 properties divided into 9 categories. Each property is associated with at least one specific European norm in which it is mentioned. In the case of certain measurable properties, an additional norm or standard is added to give the adequate measurement method

In order to further validate our work, once the RPM quality standard was finished, two data providers in the field of plastics were contacted, in order to confront the contents of our standard with their respective databases.

This comparison confirmed the thoroughness of our document, especially in terms of thermal, functional, traceability and environmental properties. Indeed, most data providers do not go into such detailed properties, which, in fact, justifies the need for the construction of such a standard.

Besides, work is still in progress to turn this document into an online database, which will allow recyclers to better communicate on their products.

4 CONCLUSIONS

A quality standard for recycled plastics has been created. It acts as a common reference for all stakeholders in the field of recycled plastics. It is designed to contain a variety of properties that thoroughly describe a grade of recycled plastic. Furthermore, EEE producers can access thorough information on these plastics, and product designers will be able to select a material based on its overall properties. This document will harmonize the communication between the recycling companies and the EEE producers, by providing a common reference for the evaluation of the quality of a recycled plastic. The RPM quality standard also links each property necessary to assess the grade of a recycled plastic with a measurement standard and a norm in force in Europe.

It appears that recyclers are satisfied with this format, as they could potentially use it to promote the use of recycled plastics to producers of plastics and EEE products by filling in multiple documents for each of their products. As for the EEE producers, they appreciate the clarity given by the document, as it lists a high amount of information on a recycled plastic batch. Thanks to the consistent information about the properties and availability of recycled plastics, this tool could offer new opportunities for EEE designers to integrate recycled plastics into new products.

However, this document remains a prototype of an online software to be developed, and harmonisation must still be achieved within the recycling companies: the testing of recycled plastic batches is still quite different depending on the financial resources of the company. Such a database would drastically improve the reach of our work, and further promote the use of recycled plastics in the field of WEEE.

To help the design teams, two ecodesign indexes have also been proposed. The first index is calculated with data from the EoL treatment chains and focuses on the recoverability of materials. The second one can be calculated directly from the RPM quality standard; it evaluates the re-integrability of materials into new products.

Both indexes were designed to be as thorough as possible, as opposed to the recycling and recovery rates currently proposed by European norms, which only focus on the mass of retrieved material.

Work is still ongoing to formally construct and validate the ecodesign method that will unite the RPM quality standard and the eco-design indexes, in partnership with stakeholders from the recycled plastics industry and official organisations.

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APPENDIX

The RPM technical datasheets are available online:
Nève, N., 2022. RPM technical sheets (Software No. 8). Chaire Mines Urbaines, France.
Location in archive : https://archive.org/details/rpm-technical-sheets

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