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Product Recoverability: A Review of Assessment Methods

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Abstract

Today, companies need to assess the recoverability of their products from the design phase, not only for legislative reasons but also to appraise how they will be able to recover all or part of their value when they reach end of life. The main reference calculation methods are both the norm ISO 22628, which addresses the automotive industry, and the IEC/TR 62635 report, which addresses the electrical and electronic equipment industry. Both reference methods only focus on mass preservation indicators (as legislation requires) but ignore important aspects such as material quality loss, environmental impacts, and economic value preservation. Indeed, multi-criteria assessment is needed as it can be a key factor for both improving product design and to help designers integrate recycled materials into their products. In that regard, several other studies exploring multi-criteria analysis (*i.e.* technical, economic and/or environmental-based) do exist. The aim of this paper is to (i) present a critical review of current recoverability assessment methods and (ii) find the existing gaps by comparing whether the used indicators meet the designer needs or not.

Keywords: Product recoverability; Multi-criteria assessment; Multi-approach assessment; Eco-design.

1. Introduction

In the 19th century, the industrial revolution led to a shift from a predominantly agrarian and artisanal society to a commercial and industrial one, leading to major technological, economic and social changes. These transformations allowed for the rise of capitalism as the dominant world economic model. This system has led to a point where consumption, blown out of proportion by a perceived need of the non-essential, exceeds basic necessities by far. This hedonistic and industrialized consumption pattern has led to environmental problems such as pollution, climate change, non-renewable resources depletion, etc.

In order to fight these problems, a new economic model known as *circular economy* has emerged. It mainly seeks to transform the traditional linear product's life cycle (*from cradle to grave*) into a closed loop approach known as *cradle to cradle*, the final goal being to recover value from waste. Indeed, when a product reaches its end of life[1] (EoL), it is still possible to recover all or part of its functional, material or energy value.

Eco-design plays an important role in the circular economy approach, as it allows the design of more ecofriendly products. One of its main tasks is product recoverability assessment, which consists of projecting potential consequences of the choices made during the design phase and their effect at the product's end of life [1].

The aim of this paper is to present a critical review of current recoverability assessment methods (see § 4) and to find its existing gaps by comparing whether the used indicators meet the designer needs or not (see § 5).

[1] In our approach, product's EoL does not necessarily mean the end of its usability (*i.e.* when it loses its functional value). It just refers to the moment it becomes waste and it can either undergo a recovery treatment or be disposed.

Nomenclature

EB	Environmental Benefice
EI	Environmental Impact
ELV	End-of-Life Vehicle
EoL	End-of-Life
EV	Environmental Value
WEEE	Waste Electrical and Electronic Equipment

2. Waste management framework

2.1. The legislation

In the early 1970s, a general interest in the environment began to take hold. Since then, several demanding and restrictive regulations have been put in place to recover waste and protect the environment.

The *extended producer responsibility* (EPR) was first promoted by the OECD (Organisation for Economic Co-operation and Development) in the 1990s. It is based on the principle that the producer of a product is responsible for it throughout its entire life cycle, and therefore also at the end of its life. They are thus responsible for financing and managing the treatment of their products once they become waste.

The Waste Framework Directive or Directive 2008/98/EC [2] sets the basic concepts, definitions and principles related to waste management, in particular a waste management hierarchy: prevention, preparing for reuse, recycling, other recovery (*e.g.* energy recovery), and disposal. Moreover, the *polluter pays* principle and the EPR are established.

Today, several product specific regulations exist (*e.g.* Directive 2000/53/EC [3] for end-of-life vehicles (ELV) and Directive 2012/19/EU [4] for waste electrical and electronic equipment (WEEE)). They promote the creation of take-back schemes within Member States to improve EoL waste management. Their performance is usually measured by the collecting, recycling and recovery rates.

Regulations also encourage manufacturers to engage in eco-design approaches to prevent waste generation and to improve EoL recovery [2,5]. In that regard, the concepts of reusability, recyclability and recoverability, and their corresponding rates were first addressed by the automotive industry with the European Directive 2005/64/EC [6], which completes the ELV Directive.

2.2. The EoL treatment chain

Here, we focus on the stakeholders' network responsible for treating the waste, referred to in this article as the EoL treatment chain. It can be defined as *the distributed industrial system whose scope of action is limited by legislation and which aims to (i) preserve the added value of the product, (ii) reduce the impact of raw materials extraction and (iii) reduce the amount of waste incinerated or landfilled. This system integrates on one hand, all treatment processes and actors (internal and external) responsible for preserving the added value of the product, and on the other hand, all material, capital and information exchanges* (adapted from [7]).

3. Product design framework

3.1. The product design cycle

Design is the set of processes that transforms requirements into the specification of a product, process or system [8]. The product design cycle is composed of the following steps [9]:

Task clarification. The purpose of this phase is to identify and express the needs. Product's main functions and constraints are set out in the form of a requirements list.

Conceptual design. This phase aims at specifying the principle solution. Many concepts are developed to answer the needs previously listed, then compared to assess issues that could potentially arise. A principle solution is thus selected.

Embodiment design. In this phase designers firm up the selected principle solution by determining the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (components shapes and materials) and the production processes. The most suitable solution from technical and economic points of view is chosen.

Detail design. In this phase, the embodiment of the product is completed and documentation is elaborated (production, assembly, transport and operation instructions).

Industrialization. Lastly, this phase aims to both validate the solution and to optimize manufacturing processes. Prototypes of the product are built and tested.

3.2. Eco-design and eco-designer needs

Eco-design is the integration of environmental aspects into product design, with the objective being to reduce the negative environmental impacts throughout the product's life cycle while rendering an equivalent or greater service [8,10]. This approach aims to find the best balance between technical, economic, environmental and social requirements [10].

The designer therefore needs (i) a way to assess the compliance of the technical, economic, environmental and social requirements and (ii) a way to verify that the best balance between those requirements has been found. In that regard, product recoverability is frequently used to evaluate product design. Indeed, in contrast to recovery assessment, which focuses on determining the performance of a reference EoL treatment chain that treats a set of products; recoverability assessment estimates the way a product is going to be processed by the reference EoL treatment chain once it reaches its end of life.

4. Product recoverability assessment

The aim of this study is to identify the existing product recoverability assessment methods and the corresponding indicators and to verify whether they respond to the designer needs. To that end, we researched methods assessing recoverability or recyclability in the literature. Then, they were compared (see Table 1) based on the indicator's characteristics: type, approach, and considered EoL scenario. Product designers are not the only ones for whom recoverability indicators are intended, and so the destined user and the stage at which the indicator is supposed to be used are also taken into account.

4.1. Recoverability definition

Before determining the best way to assess product recoverability, the term itself has to be defined.

The Directive 2005/64/EC defines it as the potential for recovery of component parts or materials diverted from an end-of-life vehicle [6]. For the norm ISO 22628, it is the ability of component parts, materials, or both that can be diverted from an end-of-life stream to be recovered [11]. A similar definition is given by the IEC technical report (IEC/TR 62635), which considers it as the ability of a waste product to be recovered, based on actual practices [12]. A more complete definition is provided by Mathieux *et al.*, they define it as the ability of the product, its components and the constitutive materials either to be reused, or to be recycled or to be recovered as energy [13].

Some complementary definitions might be those related to recyclability. Villalba *et al.* define it as the ability a material has to reacquire the same properties it originally had [14]. For Maris *et al.*[15], it is the capacity of an EoL product and a reference network to restore materials, technical properties and economic value close to those of its origin.

As can be seen, recoverability is usually related to reusability, recyclability and energy recoverability. However, the notions of functional, material and energy value preservation might be more apt as they cover other valorization possibilities (*e.g.* upgrade, solid recovered fuel, etc.) which might be ignored in the traditional EoL valorization scheme (*i.e.* reuse, recycling and energy recovery).

With the aforementioned definitions in mind, we shall define recoverability as *the ability of a product and a reference EoL treatment chain to recover functional, material, and energy value out of a product with the goal being to restore the technical properties and the economic value of the product's components and constitutive materials to those it originally had.*

Even though the environmental criterion is not mentioned in our definition, it should be taken into account, as the objective of EoL product valorization is not only to recover value but also to reduce the environmental impact (EI) linked to raw materials extraction and the manufacturing of new products. Indeed, value should not be recovered if it is overall detrimental to the environment to do so.

4.2. Reference methods for assessing product recoverability

The first reference method for product recoverability assessment is proposed by the norm ISO 22628 [11]. It defines the recyclability and recoverability rates of a new road vehicle as the weight ratio of the components and materials considered to be recyclable/recoverable, to the whole vehicle. The recyclable (reusable and/or recyclable) and recoverable (reusable, recyclable and/or energetically recoverable) masses are defined depending on the design and material properties of the vehicle and taking into account proven technologies.

The second reference method is proposed by the IEC technical report IEC/TR 62635 [12] and addresses the Electrical and Electronic Equipment (EEE) industry. Recyclability and recoverability rates are calculated by dividing the recyclable/recoverable masses of each part of the product (part mass weighted by the recycling/recovery rate of a defined EoL scenario) by its total mass.

Both reference methods use recyclability and recoverability rates for product recoverability assessment. Although, the IEC/TR 62635 method is more accurate than the ISO 22628 due to the fact it integrates chain performance rates into its calculation.

Recyclability and recoverability rates are very useful indicators as they allow an assessment of the extent to which a product's parts and materials undergo the different value recovery options (*i.e.* reuse, recycling and energy recovery). Weight-based indicators are frequently used to assess whether manufacturers comply with the recycling and recovery targets set by legislation. However, recoverability assessment using product mass as the only criterion will not ensure an efficient design [12]. Indeed, important issues such as material quality loss, consequent environmental impacts, or economic value preservation are not covered.

4.3. Other existing methods for assessing product recoverability

Several researchers in the field are working on developing further criteria and approaches to the ones listed above.

4.3.1. Single approach assessment methods

The following methods focus on a single approach assessment of product recoverability. They are sorted by the type of approach (*i.e.* technical, environmental or economic).

Concerning the technical approach, some researchers also work on assessing the mass criterion. They use a very similar calculation methodology as the one proposed by the IEC/TR 62635 [12], which is to take EoL performances into account when calculating recyclability and recoverability rates. For example, Umeda *et al.* [16] developed a design support method for improving recyclability of EEE. They use recyclability rate assessment to generate design alternatives that increase the rate by conducting impact analysis with the change of material composition and EoL scenario. The recycling rate is the weight ratio of all the recyclable components to the whole product. Similarly, Martínez Leal *et al.* [17] propose a method to obtain more realistic recyclability and recoverability rates than the ones from the ISO 22628 method: first, recycling and recovery rates of each component of a model-product (average composition of all products treated by the selected EoL chain in the analysed year) are calculated; then, they are used as performance factors to obtain the recyclability and recoverability rates of the analysed product.

Zeng and Li [18] address a technical approach from a different perspective. They developed a method for measuring the recyclability of a product in terms of the grade, diversity and entropy of the product's constitutive materials. In addition, recycling difficulty level is assessed for the purpose of dividing recycling responsibility between producer and recycler. A product's recycling difficulty is calculated in terms of materials grade and concentration within the product.

Huisman *et al.* [19] focus on an environmental approach and propose the QWERTY concept as an alternative to the traditional weight-based material recycling efficiency assessment. The aim is to relate the actual EoL treatment environmental value (EV) (*i.e.* positive or negative EI), to the realistic best case[2] and worst case[3] scenarios. The QWERTY score is the difference between the actual environmental impact (EI) to the maximum EI in a normalized scale. A complementary measure is the $\text{QWERTY}_{\text{loss}}$ score, which indicates the difference between the actual EI from the minimum EI. The grade of materials is taken into account in the recycling EI assessment indicator.

Chen *et al.* [20] work on an economic approach. They propose a cost-benefit analysis model as a tool for assessing the economics of designing for recycling. The model is based on the EoL treatment costs (*i.e.* disassembly, shredding and sorting, recycling and elimination) and the revenue of EoL treatment products (*i.e.* reusable parts, recycled materials, and energy savings). Two indicators are proposed: the cost benefit ratio and the net benefit of recycling.

Villalba *et al.* [14] propose assessing materials recyclability from the point of view of their monetary value. They consider that a material's recyclability can be estimated by its devaluation (loss of monetary value). Two indicators are proposed: the recycling index (value ratio of recycled materials to raw ones) and the devaluation (materials value loss after use).

4.3.2. Multi-approach assessment methods

The following methods use a multi-approach assessment of product recoverability.

Chemineau [1] proposes an eco-design methodology that measures product recoverability using a technical and an economic indicator:

- the *potential mass recoverability rate* which is obtained by the sum of the reuse, recycling and energy recovery rate of the analyzed component;
- the *potential recoverability profitability* which is calculated by subtracting the total treatment cost from the value of all the products obtained from the treatment process (*i.e.* second-hand parts, recycled materials and energy).

Maris and Froelich [15] propose to measure recyclability with two technical and one economic indicators:

- the *mass preservation* is determined by materials' masses and a mass efficiency indicator, obtained from materials' treatment efficiency (*i.e.* shredding, sorting and recycling);
- the *exergy preservation* is determined by materials' masses and an exergy efficiency indicator, which is constructed from the loss of exergy due to the mass loss, impurities and the addition of raw material for dilution;
- the *economic value preservation* is determined by materials' masses and an economic efficiency indicator, representing materials value preservation after recycling.

In addition, the method highlights the importance of scope definition, namely, the difference between materials obtained after shredding and sorting (secondary materials) and the ones obtained after recycling (secondary raw materials). Impurities in mass efficiency rate assessment are also addressed.

Ardente and Mathieux [21] propose the REAPro method which allows to assess and improve the resource efficiency of energy-using products. The proposed indicators are:

- the *reusability, recyclability, and recoverability rate*, whose structure is consistent with the formulas of the IEC/TR 62635 [12] (see § 4.2);
- the *reusability, recyclability and energy recoverability benefit rates*, which are all ratios of the EV (*i.e.* environmental impact (EI) or benefice (EB)) of the treatment activities (*i.e.* reuse, recycle or energy recovery) to the EI of a single life product life cycle (raw materials production, manufacturing, use, and elimination);
- the *recycled content*, which is the ratio of the recycled materials contained in the product to the product mass;
- the *recycled content benefit rate*, which is the ratio of the EV due to the use of recycled materials to the EI of a single life product life cycle.

Ardente *et al.* propose ENDLESS [22], a multi-attribute decision-making method seeking to help the designer choose the product with the highest recyclability potential. This method uses a global recycling index (GRI) to assess the recyclability potential of products. It is obtained by weighting and merging three sub-indexes: energy and environmental, economic, and technological (not detailed by the authors). Decision makers have to choose the appropriate set of product structure alternatives, evaluation parameters and calibrate the model (*i.e.* estimate the weights) to fit their particular needs.

Mathieux *et al.* [13] propose the ReSICLED method. It models recovery systems and assesses multicriteria recoverability in order to promote an EoL conscious design. The method proposes a set of technical, economic, and environmental indicators:

- *the weight recovery indicator (recovery and recycling)*, which are both calculated by subtracting the treated fractions not going to the desired destination from the product mass, and then divided by the product mass;
- *the economic recoverability indicator*, which is calculated by the subtraction of the economic benefits associated with selling the products of EoL treatment (recycled materials an energy) from the cost of all EoL treatment processes;
- *the environmental impact recoverability indicator*, which is obtained by dividing the EV (EB of the use of recycled materials and recovered energy minus the EoL treatment processes EI) by the product manufacturing EI.

The synthesis of all the analysed product recoverability assessment methods is presented in Table 1.

[2] The best EoL scenario (minimum EI) corresponds to all materials being recovered completely without any environmental impact.

[3] The worst EoL scenario (maximum EI) corresponds to every material ending up in the worst possible (realistic) EoL route.

Table 1. Product recoverability assessment methods comparison.

				Type		Approach				EoL scenario				Use phase			Intended user						
Method	Author	Year	Indicator	Quantitative	Qualitative	Technical	Environmental	Economic	Other	Proven technologies	Realistic defined by the user + database	Realistic defined by tool + database	No consideration of EoL	Design	Post design	Unspecified	Designer	Ecodesign expert / EoL expert	Producer (unspecified)	EoL chain stakeholders	Gov. (policy makers, env. agency)	Other	Unspecified
-	Chen et al. [20]	1993	Cost benefit ratio of recycling	x				x			x			x			x						
			Net benefit of recycling	x				x			x			x			x						
ISO 22628	ISO [11]	2002	Recyclability rate	x		x				x					x				x				
			Recoverability rate	x		x				x					x				x				
-	Villalba et al. [14]	2002	Recycling index	x				x			x					x							x
			Devaluation	x				x			x					x							x
ENDLESS	Ardente et al. [22]	2003	Global recycling index	x		x	x	x			x			x			x						
QWERTY	Huisman et al. [19]	2003	QWERTY	x			x				x			x	x		x			x	x		
			QWERTY loss	x			x				x			x	x		x			x	x		
ReSICLED	Mathieux et al. [13]	2008	Weight recovery (recycling)	x		x					x			x			x	x					
			Weight recovery (recovery)	x		x					x			x			x	x					
			Economic recoverability	x				x			x			x			x	x					
			Environmental impact recoverability	x			x				x			x			x	x					
-	Chemineau [1]	2011	Potential mass recoverability rate	x		x								x				x					
			Potential recoverability profitability	x				x						x				x					
IEC/TR 62635	IEC [12]	2012	Recyclability rate	x		x					x			x			x						
			Recoverability rate	x		x					x			x			x						
-	Maris et al. [15]	2013	Mass preservation	x		x					x			x			x						
			Exergy preservation	x		x					x			x			x						
			Economic value preservation	x				x			x			x			x						
-	Umeda et al. [16]	2013	Recyclability rate	x		x					x			x			x						
REAPro	Ardente et Mathieux [21]	2014	Reusability rate	x		x					x				x						x		
			Recyclability rate	x		x					x				x						x		
			Recoverability rate	x		x					x				x						x		
			Reusability benefit rate	x			x				x				x						x		
			Recyclability benefit rate	x			x				x				x						x		
			Energy recoverability benefit rate	x			x				x				x						x		
			Recycled content rate	x		x					x				x						x		
			Recycled content benefit rate	x			x				x				x						x		
			Use of hazardous substances		x		x				x				x						x		
-	Martinez Leal et al. [17]	2016	Recyclability rate (realistic)	x		x						x		x			x						
			Recoverability rate (realistic)	x		x						x		x			x						
-	Zeng et Li [18]	2016	Recyclability	x		x							x	x	x				x				
			Recycling difficulty	x		x							x	x	x				x				

5. Conclusions and perspectives

Researchers have identified that product recoverability mainly depends on product design characteristics (*e.g.* structure, material composition, weight, accessibility, lifespan, integration of reused components and materials, etc.) and the characteristics and performances of EoL treatment processes (*e.g.* treatment flow, cost, environmental impact, recovery rates of each product, part and material, and mass, quality and economic value losses) [12,13,15,16,23–26]. EoL feedback information is usually obtained via the definition of an EoL treatment scenario that is subjected to the scope of calculation and the geographic and temporal validity of EoL scenario data [12,15]. It has also been noted that the designer needs to take into account the recycled materials outlets [15].

The designer needs a scientific and quantitative assessment of the ability of a product to be recovered, concrete guidelines for the design team, and the design solution space kept as large as possible [13].

Concerning product recoverability assessment, all the aforementioned indicators can be classified as either a technical, environmental or economic approach (see Table 1). Technical approaches are the most widely used means for assessing product recoverability (implemented in 76% of the methods). Environmental and economic approaches are also common (30% and 46 % respectively).

Technical approach indicators can be grouped in five categories: recoverability rates (*i.e.* reusability, recyclability, energy recoverability and recoverability rates), recycled content rate, recycling difficulty, material quality preservation and product recyclability. Weight-based indicators have been widely used and developed over the years. Today, the IEC calculation method seems to be accepted by researchers as the reference method. Indeed, these indicators, along with the recycling content rate, seem to be sufficiently developed and accepted by the community. In contrast, material quality preservation, recycling difficulty and product recyclability are less commonly used indicators, though they may be useful design tools in future.

Among the environmental approaches, EI assessment is the commonly accepted indicator. However, the calculation may vary from one method to another.

In the economic approaches, the proposed indicators are the potential profitability (or net benefit), the cost-benefit ratio, the recycling index and the devaluation. The first two are focused on assessing the EoL treatment chain viability and the last two on materials price relation.

To summarize, the designer needs to find the best balance between technical, economic and environmental requirements. While the indicators found in the analyzed methods already cover the three criteria, tools capable of finding the best balance between those requirements are still missing.

In addition, almost all these methods are based on the definition of a realistic EoL scenario by the user. This generates uncertainty in the results and it is therefore important to reduce it by developing a method whose results are not user-dependent.

Finally, the construction of EoL treatment performances databases is needed. In the EU context, mass performances are already being declared. However, exhaustive EoL EI databases and easy assessment tools are needed (*e.g.* [27,28]), so that the designer no longer needs to be an expert on EoL.

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