CRITICAL ANALYSIS OF EXISTING RECYCLABILITY ASSESSMENT METHODS FOR NEW PRODUCTS IN ORDER TO DEFINE A REFERENCE METHOD

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Keywords: Recyclability, standard, ecodesign.

Abstract

The designers of products subject to the European regulations on waste have an obligation to improve the recyclability of their products from the very first design stages. The statutory texts refer to ISO standard 22 628, which proposes a method to calculate vehicle recyclability. There are several scientific studies that propose other calculation methods as well. Yet the feedback from the CREER club, a group of manufacturers and suppliers expert in ecodesign and recycling, is that the product recyclability calculation method proposed in this standard is not satisfactory, since only a mass indicator is used, the calculation scope is not clearly defined, and common data on the recycling industry does not exist to allow comparable calculations to be made for different products. For these reasons, it is difficult for manufacturers to have access to a method and common data for calculation purposes.
A critical analysis of the standard and the various calculation methods identified in scientific journals was performed. An initial discussion brought to light several possible scopes of calculation. Additional indicators, such as quality loss or economic value loss, would be complementary to the mass indicator. Case studies were performed to compare these different methods. A new method and its scope of calculation are proposed in order to develop a reference method.

Glossary

ELV: End-of-life vehicle

WEEE: Waste Electrical and Electronic Equipment

PRM: Primary raw material

SM: Secondary material

SRM: Secondary raw material

Introduction

The European directives on end-of-life product treatment are now in application. The assessment of recycling networks in terms of the quantities collected and the efficiency of the treatment and recycling is one of the objectives of the statutory texts. Recycling efficiency will be improving in the near future thanks to the use of increasingly successful sorting and transformation technologies. But this is not sufficient. Companies must have an ecodesign strategy for their new products that integrates the constraints of recycling in order to improve the efficiency of end-of-life product treatment.

This strategy must also integrate the use of recycled materials, provided that there are important and long-lasting sources as well as good quality materials; this is the case today for certain materials, but not all.

The European directives contain a recyclability calculation reference based on standard 22 628 [1] for automobiles, while proposals of standards for WEEE and earth-movers are still under discussion. However, a report drafted by industrial members of the CREER club indicated that the product recyclability calculation method used in this standard is not satisfactory, for the following reasons:

- The scope of calculation is not defined,
- The data on treatment networks does not exist or is not capitalized in a common data base,
- The mass recyclability indicator does not suffice to estimate the quality of the materials produced.

For these reasons, it is difficult for industrialists to have access to a method and common data for calculation purposes.

The objective of this study is to examine the state-of-the-art recyclability calculation methods for new products, with the aim to define a reference method for designers.

The study is exploratory and includes 4 sections:

- Critical Analysis of the definitions of product recyclability and principle proposal for the calculation of recyclability
- Proposal of the indicators of mass, properties and economic value
- A case study

Critical Analysis of the definitions of product recyclability and principle proposal for the calculation of recyclability

Critical analysis of definition of definitions in the European directives and standards

The 22 628 standard on recyclability calculation and vehicle recovery defines recyclability as the capacity of components, materials or both to be removed from the end-of-life flow to be recycled. The recyclability rate is the percentage of the mass of a new vehicle that can be recycled, potentially re-used or both. The recyclability rate thus includes recycled material and re-used components. Recycling is defined as the recovery of waste from products, materials or substances for the same purposes as their initial function or for other purposes, excluding energy recovery.

Recyclability rate	
Re-use of component parts	Recycling of materials

The standard does not indicate whether the calculation should be made in relation to a regulated reference network. A product should be considered as recycled when there is a representative recycling network that is economically viable at the national or European level. Regulated networks exist in Europe and are financed by consumers through eco-taxes on products that are redistributed in eco-friendly waste management networks. These networks accept several types of products. ELVs are accepted and represent up to 40% of the incoming products for shredding facilities. Certain products such as furniture and high voltage WEEE are not subject to regulations. It is therefore difficult to estimate their recyclability in a regulated network.

There are at least two differences between the notions of recyclability and recycling.
The first difference is that the recycling rate estimates a network treating a set of products while the recyclability rate estimates the ecodesign of a product when the latter is treated in a network.
The second difference is the product lifespan; for example, small electric equipment products will arrive at their end of life after 5 years on average, versus 15 years for vehicles. The recyclability of a product is the efficiency of a reference network with regard to the design of a product that will be treated at its end of life, with the end of life varying according to product.

The notion of recyclability is used in Directive 2005 / 64 / CE concerning vehicle re-use, recycling and recovery possibilities. It is not referred to in all the directives and is not harmonized in the various texts.
The definitions of the recycling rate also differ according to directive. For example, Directive 94 / 62 / CE concerning packaging and packaging waste defines the recycling rate as the total quantity of waste from recycled packaging divided by the total quantity of packaging waste produced. It does not indicate in which recycling step the material is considered to be recycled, incoming or outgoing?

A product designer has several scopes (see Figure 1) to take into account in order to calculate the recyclability of his product, and several questions to ask:

- How can one integrate a product lifespan if one does not know the efficiency of the network at the product's end of life?
- Is it necessary to integrate the re-used components?
- What scope of calculation should be used? Is it necessary to stop at the SM or the SRM step, i.e. components or components restored to their original level?
- What type of outlet exists for the recycled material?

The design of a product has effects on the mass efficiency and the purity rate of its separate fractions as well as on the outlets for the materials. It is necessary to define more reference treatment scenarios for every product, i.e. typical networks, and more successful indicators to help designers to integrate the end-of-life recycling constraints of their products.

<u>Conclusions:</u>
It is thus necessary to define:

- Recyclability indicators estimating the preservation of the mass and quality of the secondary raw material with regard to the primary raw material
- A reference network for a product
- A scope of calculation

We can say that a product's recyclability is the capacity of a product and a reference network to restore the materials, the technical properties and the economic value close to those of its origin when a product arrives at its end of life.

Principle proposal for the calculation of product recyclabilty

Proposal of indicators

The relevant criteria for network efficiency are thus:

- The preservation of the mass of the primary raw material (PRM) with regard to the mass of SRM
- The preservation of quality, which is translated as the preservation of properties and the preservation of the economic value of the SRM with regard to the PRM.

Proposal of a reference network

Reference networks are regulated networks in which products are collected. For example, household electrical appliances such as vacuum cleaners, coffeemakers etc. are collected and treated all together.

Regulated networks exist for:

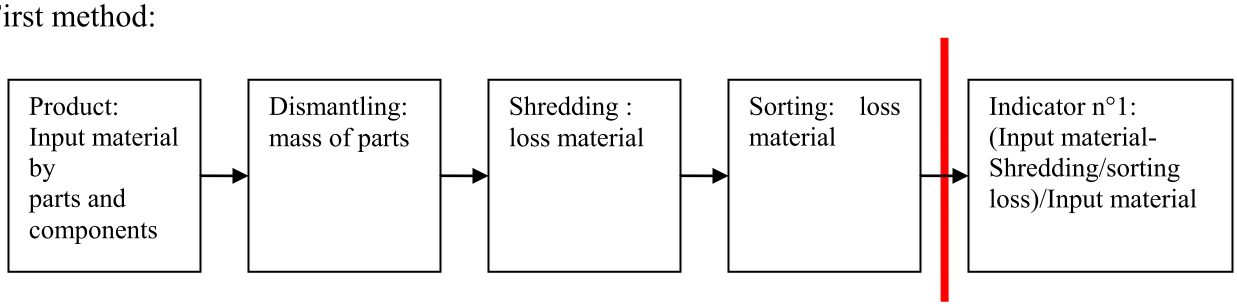
- ELV
- WEEE
- Packaging
- Boats,
- Airplanes,
- Construction and demolition waste
- etc.

There are two possible scopes and three ways to calculate the mass recyclability rate.

Proposal of a calculation scope

The first scope complies with the vision of the 22 628 standard, and there are two methods for its calculation.

First method:



Comments:

Indicator n°1, which expresses the quotient SM/input material, differs from the recycling rate measured in the field. By not taking into account the rates of impurities in the SM, in certain cases mass indicators are superior to 1 because both the impurities and the main material are counted together.

Indicator 1 does not reflect the quality losses due to the impurities of the SM and the mass losses during the recycling by melting of the SM to produce MPS (ingots). These losses depend on product design. For example, if the designer chooses to make a massive part from aluminum or aluminum sheets. The association of materials resulting from design choices that generates these losses is not taken into account.

In the calculation of the mass of dismantled parts, market demand and the waste generated during part renovation are not taken into account.

It is easy to calculate this indicator from data supplied by professionals, yet it is not a very precise support tool for designers with product recycling objectives.

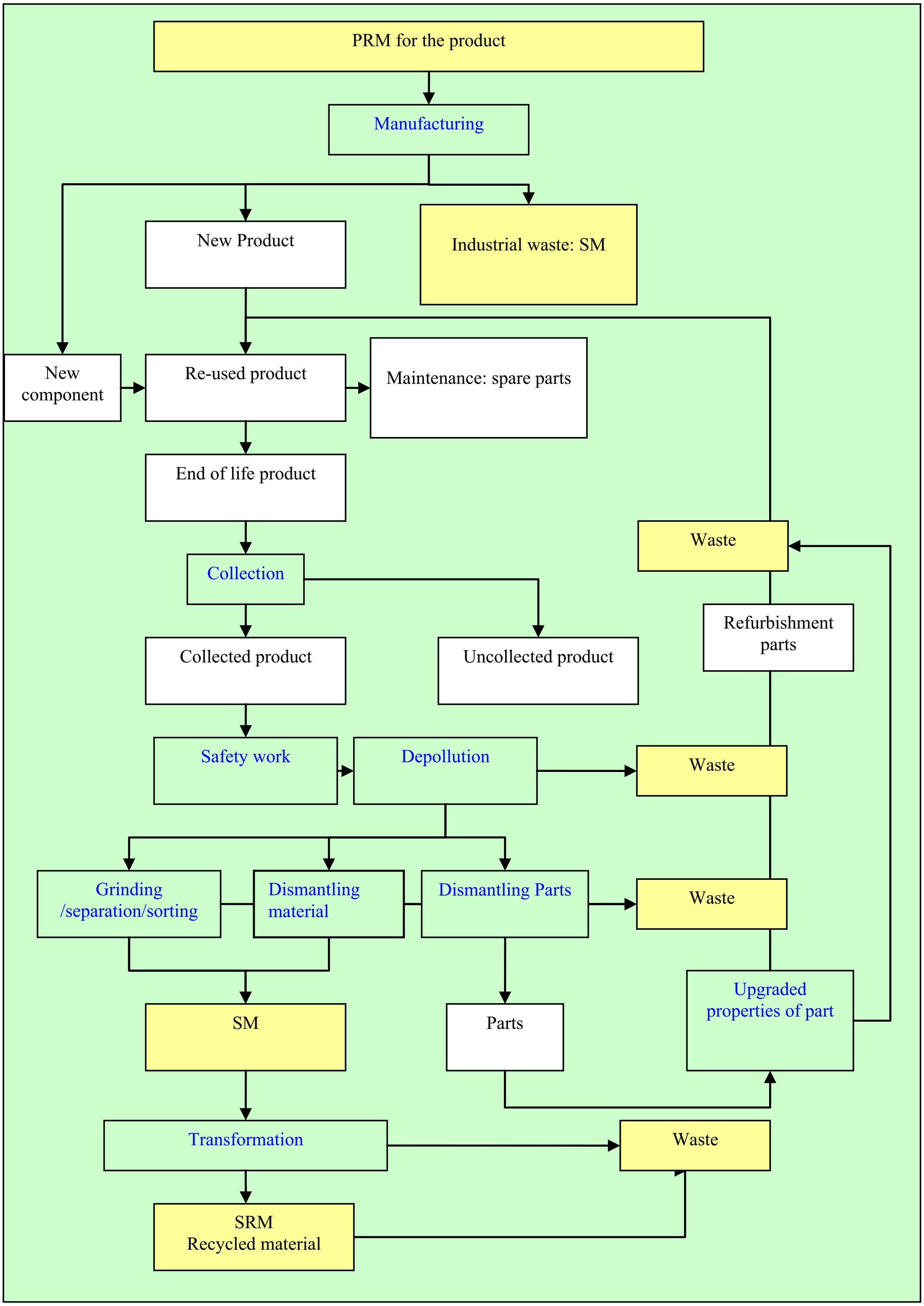
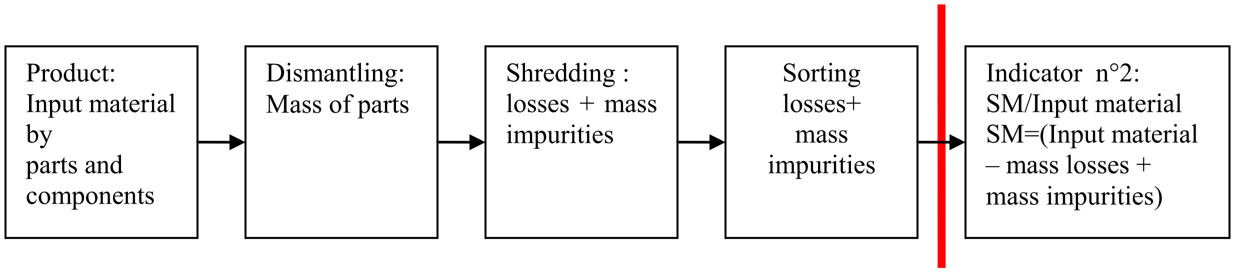


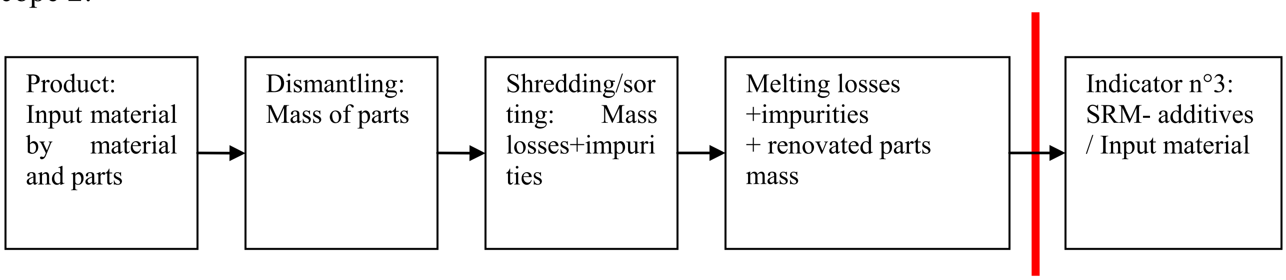
Figure 1. Definition of the scope for the calculation of product recyclability (color code: yellow: materials, white: products/components, green: transformation processing)

Second Method:
Scope 1

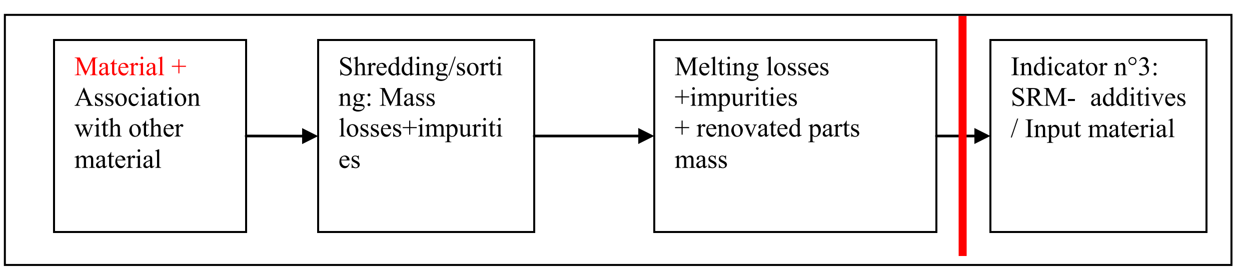


Comments:
This indicator can be linked to the measured recycling rate in the field. It is however necessary to estimate the impurity rate resulting from material associations for each type of design. This requires the use of databases built from field tests.
It also makes it possible to estimate the quality of the SM, but does not integrate the mass losses during the recycling of the SM to produce SRM.

Scope 2:



Comments:
This indicator takes into account the impurities during grinding and sorting, the SM losses and the additives added during melting to restore materials to their previous level. With regard to the previous scenario, it requires good knowledge of the main material/impurities phenomena during SM melting. This indicator is more precise for designers with product recycling objectives, since it considers the whole recycling process for various types of material associations. It is correlated with the production of secondary raw materials. Indicator n°3 can also be defined as indicated in the following diagram.



Discussion of the scopes with regard to the proposed indicators
The economic value preservation indicator becomes integrated into scope 1, since it takes into account the quality of the SM and thus the associations of materials in the design, and indirectly in scope 2 since the market prices integrate the value of the SRM. However, it takes into account the material losses at the grinding/sorting level.

The mechanical property preservation indicator takes into account the notion of SRM quality; it thus becomes integrated into scenario 2. It requires precise knowledge of all the treatment stages and the abundant thermodynamic data.

Additives and fillers added to the secondary raw material must not be taken into account.

Based on the previous hypotheses, we propose 3 types of indicators:

- A mass preservation indicator
- A property preservation indicator
- A recycled material value preservation indicator

Proposal of the indicators of mass, properties and economic value

State of the arts concerning indicators

The first difficulty when calculating product recyclability rates is to procure data on typical networks, i.e. which products go to which network, since a network treats several categories of products. The recyclability rate of a product by a network will actually be that of a set of product categories.

The second difficulty is to identify the geographical scope of a typical network. Indeed, it will be necessary for the various European countries to estimate the performances of their networks before determining which is the most successful. Today, every country is attempting to make its own technology prevail with the European Commission. The technical scope must also be taken into account. In this study, we propose that the scope include the SRM, i.e. that produced by the refiners, and the re-used parts after their restoration to standard.

The third difficulty is to procure data on the mass efficiency of the product treatment - what are the mass losses at the level of the grinding, the sorting and the melting of the materials into ingots, and how do we define the notion of mass efficiency?
In any transformation process, according to the laws of thermodynamics, mass losses occur [2]. To estimate them for each material composing a product, one must conduct shredding tests and analyze the residual product remaining in the recycled fractions as well as in the composition of the non-recycled fractions, in order to calculate process efficiency. The residuals in the recycled fractions have an effect on product quality. The quality of metals stemming from the recycling is relatively high thanks to the manual sorting which is made in Europe on the big particle size taking out crushers and in China on the more low particle size.

The mass indicator:
Work was performed to model the ELV treatment system based on grinding tests. For ELVs [2] and WEEE [3], these models integrate field data and highlight material losses for these products during the treatment stages. These losses depend on:

- Grinding particle size. This determines the rate of liberation of the associated materials [4] [5] and is different for ELVs and small electric devices. The more one crushes at the end, the more material losses there are.
- The reactivity of metals with respect to oxidation. Material losses are greater for example for aluminum and magnesium than steel.
- The material sorting, whose efficiency depends on processes and is not 100%.

- The melting to produce ingots, since the SM entering the refiner is not pure.

Because the material (metals, plastics, glass etc.) must be brought back to its original level, a dilution with virgin or recycled materials is necessary, depending on the outlets targeted. This is true for steel, diluted to decrease the brass impurity rate, which must be much lower than 0.2%. Wrought and cast aluminums are mixed after grinding because they cannot be sorted out with the existing techniques. The only application for this mixture is for cast aluminum, but a dilution is also necessary to reduce the iron impurity rate. The USGS publishes the average rates of recycled material inputs in primary metals.
For ELVs, plastics with densities between 0.9 and 1.1 are sorted out at the industrial level by certain recycling companies, but this is not a typical technique at the European level. The PP sorting efficiency communicated by the shredder company Galloo in 2001 was 44%. To satisfy noble outlets, the purity rate must reach 97% (with overall property losses lower than 5% [6]). Plastic sorting is not widespread in Europe today, since crusher companies' know-how concerns mainly metal recovery, and practically not at all that of plastics. Crushers did not anticipate the changes in product design, which has been incorporating increasingly less metal and more plastic for several years now. Yet due to the ELV lifespan, plastic must increasingly be taken into account today when recycling.

In standard 22 628, product recyclability is a standardized calculation, similar to an efficiency calculation for recovered materials. Due to the lack of data concerning the composition of the output of crushed and sorted fractions, the mass losses and the impurity rate are neglected in the calculations. Our bibliographical research shows that these two types of data are not insignificant. An outgoing fraction "A" can be larger in quantity than the incoming fraction due to the impurities. In theory, to calculate the mass efficiency one should take into account the rate of losses of the incomers and the impurities rate, just as in any efficiency rate calculation.
Mass efficiencies differ according to product. The mass efficiency of electronic products is lower than that of ELVs, with higher impurity rates. On the other hand, it includes significantly more precious metals. Plastics are styrenics containing toxic flame retardants, which depreciate their value if not sorted out.
For all of the reasons evoked above, one must take material associations into account when calculating recyclability.

<u>Economic indicator:</u>
The economic indicator can be a good way to express quality loss [7] [8] [9]. This indicator depends on the degree of development of recycling techniques as well as on the costs generated by recycling processes. We assume that this indicator is reflected by the monetary value of the recycled and virgin materials. The closer the value of the recycled material to the virgin material, the higher the recyclability rate. If this indicator is used by an engineering consulting firm, the designer can determine which types of economic outlets exist after recycling.
Since the quoted market prices of raw and recycled materials are volatile, the annual average prices of the secondary primary and primary raw materials as well as the trend curves for price evolutions during periods of at least 10 years is taken into account.

<u>The property indicator:</u>
The quality preservation indicator for the properties can be estimated using the exergy conservation indicator. Any irreversible process causes a loss of exergy leading to a reduction of the useful effects of the process, or has an increase in energy consumption. The data for exergy calculation is stable and fixed with regard to the economic values. This indicator can be

calculated with software. We can thus calculate the exergy losses due to mass loss, contamination with impurities, and dilution [10] [11] [12] [13].
In this context and using the available data, the recyclability of several products was calculated using these three indicators.

Conclusions

Conclusion 1:
There are two ways to calculate the material efficiency:
If we consider the input material and the SM, then the efficiencies can be greater than 1, which is incompatible with an efficiency calculation,
If we consider the incomers, the SM and their impurities, and the losses during transformation into ingots, then the efficiencies are lower than 1. [14]

Conclusion 2:
There are several types of mass losses during the product treatment cycle producing the secondary raw material [15] [16]:
- During the grinding, due to oxidation for reactive metals,
- Through the imperfect liberation of the associated materials,
- During the melting to produce ingots

Conclusion 3: The mass losses during the grinding / sorting / melting are not insignificant and vary depending on the metal.

Conclusion 4: the rate of liberation of the associated materials, as for ferrous metals, copper and aluminum, is different for ELVs (99, 89, 88%) [2] and WEEE (94, 78, 82%) [16]. It is lower for the electronic products. The losses of ferrous metals, copper etc. thus differ depending on the network.

Conclusion 5:
There is a difference between a product's mass recyclability and its mass recycling rate in the real networks [17]:
Example: Small household and electronic appliances:
- Theoretical mass recyclability rate: 82%, versus recycling rate achieved by the networks: 73%,
- Recycled metals: 73.2% versus 61%, MPS produced efficiency: 90% on average,
- Recycled plastics: 19% versus 7.2%, MPS produced efficiency: 38% on average.

Conclusion 6: the material efficiencies (SM/material/incomers) are different according to the type of equipment because the associated materials are different:
- Large household appliances, mass efficiency: ferrous: 99%, non-ferrous: 94%, plastic: 74%,
- Small electrical household appliances: mass efficiency: ferrous: 96%, non-ferrous: 98%, plastic: 38%.

Conclusion 7:
Metals and plastics are alloys. After grinding and sorting, alloys are mixed, for example aluminum, zinc, iron, copper alloys, etc., with the following consequences:[10]
- Material property losses
- Value losses: alloys have different values when they are mixed,

- Resource losses due to the dilution.

Conclusion 8:
According to the laws of thermodynamics [15], the efficiency of a transformation cannot be 100%, and the increase in mass efficiency occurs to the detriment of quality preservation. It is thus necessary to optimize the mass indicator and the quality preservation indicator (exergy) according to the economic outlets and thus to the economic value preservation indicator. In the future, it will also be necessary to take into account the irreversible contamination that accumulates in metals since they all include a fraction of recycled metals.

Conclusion 9:
According to the hypotheses taken into account to calculate a quality preservation recyclability indicator based on the economic value losses of the SM [8] [9]:

- The loss in value of recycled materials depends on the raw material value. Precious metals lose less value when they are recycled (mining/extraction costs quotient and recycling costs),
- The economic value of a recycled material depends on its quality, since recycled materials with properties close to the virgin material have values that are close but always lower,
- The loss of value depends on the use which is made of the SRM in a product.

Conclusion 10:
The application of the recyclability calculation methods from our bibliographical research shows that calculating recyclability according to standard 22 628 results in a significant underestimation and sometimes in an unrealistic image of the real recyclability.

<u>Proposal of a recyclability calculation method</u>

Three types of losses were highlighted during the treatment of end-of-life products with a recycling objective:

- loss of mass due to material losses,
- quality losses due to the association of materials, which has the effect of creating impurities after grinding (imperfect liberation) and sorting,
- economic value losses due to the material specificities and to their uses in a product; this indicator is also a quality indicator.

From the bibliographical research, three indicators and their calculation methods were tested for case studies. These indicators enable assessment of a product's recyclability:

1. Mass preservation indicator, Rm,
2. Exergy preservation indicator, Re,
3. Economic value preservation indicator, Rv.

The data used to calculate the economic value preservation recyclability indicator was updated for the year 2007. Databases for exergy preservation allow exergy calculation for any compound made from the chemical elements.
The recyclability of a product is ideal when these indicators approach 1.

The mass preservation indicator Rm is determined according to the mass efficiency ξmi (see Table 1) and is specific to every material during the various stages of the treatment of end-of-life products.

$$R\ m = \Sigma\ mi * \xi mi / \Sigma\ mi$$

- Rm: Mass preservation indicator,
- Mi: Mass of each material i (kg),
- ξmi: Mass efficiency indicator specific to a network and a material,

ξmi is the product of the mass indicators for the shredding (grinding), sorting and refining, ξmi= ξg* ξs* ξr,

- If ξ = 0, no recycling in SRM or re-use.

For product re-manufacturing:

$$R\ m = \Sigma\ \xi mi\ parts * Market\ share$$

Table 1. Mass efficiency indicators

Accepted material	Unaccepted material	Refused material	Dismantled parts
ξm > 0 % recyclability	ξm = 0 No recyclability	ξm≥ 0 obligatory dismantling + restoration to standard, % recyclability	ξm ≤1 restoration for re-use % recyclability

The exergy preservation indicator Re, determined according to the loss during recycling, is estimated using the exergy efficiency indicator ξe.

$$Re = \Sigma\ mi * \xi e = Rm * \xi e$$

$$\xi e = e\ srm / e\ srm$$
$$e\ srm = em + ei + ed$$

- Re: Exergy preservation indicator,
- em: Loss of exergy due to the mass loss (MJ/kg),
- ei: Loss of exergy due to impurities (MJ/kg),
- ed: Loss of exergy due to the addition of virgin material for dilution in order to restore to the SM standard.

Comment: Aspect or color quality losses cannot be estimated using the exergy. In this case, they are taken into account in the ENSAM/Renault method [6].

The economic value preservation indicator Rv is determined with respect to the economic efficiency indicator ξv ", which estimates the preservation of the material's value after use and recycling.

$$\mathbf{R_v = f(Vprm, Vsm, Vsrm)}$$
$$\mathbf{= \Sigma m_i}\ \xi v\ \mathbf{/ \Sigma m_i}$$

Vprm: PRM value ($/kg),
Vsm: SM value (/kg),
Vsrm: SRM value (/kg),

ξv: Economic efficiency. When it is equal to 1, this means that the value of the secondary raw material is practically equal to that of the primary raw material. The values for various materials are expressed in the graph in Figure 2.

$\xi v = 1$ if R=[0.8 ;1],
$\xi v = 0$ if R=[0 ;0.8],
The value of 0.8 was chosen as a threshold.

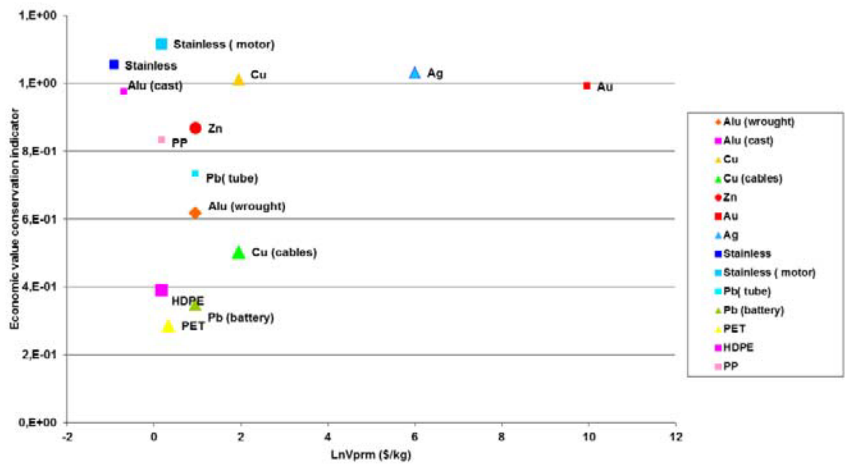


Figure 2. Economic value preservation indicator (updated in 2007) [8] [9]

Comment:
According to the laws of thermodynamics, the efficiency of a transformation cannot reach 100%, and any decrease in mass losses occurs to the detriment of material quality preservation. It is thus necessary to optimize the mass losses and the quality preservation according to the economic outlets and thus to the economic value preservation.

These three indicators (see Table 4) are defined for typical networks, for example for ELVs or WEEE. The mass indicator for the ELV network is higher than that of the WEEE, according to the studies quoted previously. However, for certain electronic products containing precious metals, the economic indicator can be higher.

Table 4 . Product recyclability defined by the preservation of mass, quality and economic value efficiency

Accepted material	Unaccepted material	Refused material	Dismantled part	Mass efficiency	Exergy efficiency	Economic value efficiency
ma_i	mi_i	mr_i	md_i	$\xi_i = \xi_g * \xi_s * \xi_r * \xi d_i$	$\xi_e = e_{srm} / e_{prm}$	$\xi_v = \Sigma m_{i\ R=(0,8\ ;1)} / \Sigma m_i$

Case study

The bibliographical research made it possible to identify indicator calculation methods estimating the performances of end-of-life product recycling as well as the quality and value of the recycled materials produced. To calculate these various indicators, one must collect data on the mass balance assessment of the dismantling, crushing and sorting as well as the material losses up until ingot production by the network operators. This data is still unknown, but certain studies have modeled the efficiency of the systems. The databases and software used to calculate these various indicators are not always available. For these reasons, it was not possible to test all of the methods. As an illustration, mass recyclability according to the standard is compared with the mass recyclability integrating losses during the transformation process and a scope including the production of SRM.

Case study: a car body part

Hypothesis: A car body part (Figure 4) is dismantled. It has a steel core and an aluminum cover. During the grinding / sorting, the steel and the aluminum are not separated; the fraction after sorting is captured in the ferrous fraction, due to the ferrous mass. During material melting in an electric oven, the aluminum is oxidized since it is associated with the steel and thus is found in the slag, and it is therefore not recycled. Only the steel is recycled.
In the recyclability calculation, standard 22 628 does not require that the parts be treated in a representative network.

If there is at least one process allowing treatment of this part, the recyclability rate is considered to be 100%.

In the case of the car body part, the mass recyclability (see Table 3, 4) is 47%, because there are losses at the level of the separation by grinding but especially during the melting. The indicator takes into account the material associations.
The economic value preservation indicator does not take into account mass losses due to the melting but it does take into account the loss of value of the SM, in this case the aluminum in the second melting. With respect to the primary raw material, this loss is significant for the aluminum. The recyclability of the body part is 48%. The mass indicator and exergy preservation is 35%; it takes into account the losses during the steel refining.

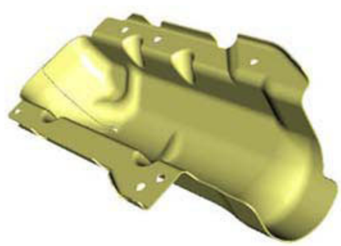


Figure 4. Case study: a car body part

Table 2. Recyclability according to standard 22 628, mass, economic value and exergy preservation indicators

Car body part: ELV channel	Mass (kg)	ξ % Standard	R Standard	ξ Mass%	R Mass	ξ v%	R Economic value	ξ exergy %	R exergy
Steel	0.17	1	0.48	0.98	0.47	1	0.48	0.74	0.35
Wrought Aluminum	0.18	1	0.52	0	0	1	0	0.8	0
Total	0.35	1	1		0.47		0.48		0.35

Table 3. Calculation of the mass efficiency

Car body part: ELV channel	ξ oxidation	ξ Separation	ξ Melting	ξ m total
Steel	1.00	0.99	0.99	0.98
Wrought Aluminum	0.91	0.88	0	0

Summary of the case study:

According to the calculation method used in the standard [1], for a product to be recyclable, a process or network must exist that allows every component or material in the product to be recycled. The scope of calculation takes into account the input materials/components and does not take into account the shredding, sorting, and refining processes leading to the production of SM and SRM. In the case of a car body part, recyclability is considered to be 100%.
If the recyclability calculation is carried out with a scope covering the MPS, the results are quite different from the standard.

This calculation is often very far from reality, as shown by our comparison of the various recyclability calculation methods tested in the case studies. There are indeed several types of losses.

Conclusion

This study shows that the recyclability calculation method according to standard 22 628 is not satisfactory for designers as concerns the scope of calculation. In order to make more relevant choices of materials and their associations to improve product recyclability, we recommend that they choose a scenario with a calculation scope covering the production of secondary raw materials.
This scenario allows more realistic theoretical product recyclability calculation and responds to the European ratification objectives. As for the quality preservation approach, a first step is to use an economic indicator to guarantee the sustainability of a recycling network. Secondly, when recycling processes can be better modeled, it will be possible to apply a quality indicator based on the notion of exergy, which we consider more reliable from an environmental standpoint.

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