Determining a Recyclability Index for Materials

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Summary.

One of the major challenges we face as a society is to meet the needs of the present without compromising the ability of future generations to meet theirs. The increasing economic activity over the last decades has resulted in increased demand of materials. To be able to meet this challenge, one of the major tasks is to close the material cycle. Therefore recycling or reuse of materials has become a priority, and a joint effort from all disciplines. However, what seems to be missing is a clear definition of recyclability, or a way of measuring the recyclability of materials.

The objective of this work is thus to define recyclability in such a way that a recyclability index of materials can be determined. The recyclability index depends on both extrinsic and intrinsic properties, but it is determined based on the market values of the material at different stages of its life cycle. This measurement can be used as a parameter in many applications such as material selection, design for disassembly and other applications whose aim is to close the material cycle.

The recyclability index is a useful tool, however it has its limitations. For example, it is deduced from historical data, and it is sometimes difficult to determine because prices for post-use and post-recycled materials are not always available. More data would be useful to corroborate the relationships here established.

Introduction.

Closing the material cycle has become a top priority and a multidisciplinary effort. Manufacturers need to meet the recycling requirements imposed upon their products. Engineers and designers[1], study how to incorporate recycling in product design for better disassembly, for increased recycling, remanufacturing, and reusing components of products. Governments and institutions analyze models to compare costs of recycling and benefits of environmental protection actions. Recycling and economics are tied: if there are no markets for recycled materials, recycling is doomed to failure (Folz, 1991).

There is a missing common factor that is of crucial importance to all these disciplines: the need for a definition of recyclability and a way of measuring the recyclability of materials. There is no consensus on how to measure recyclability right now. What some call recycling others consider reusing[2]. There needs to be a measurement of recyclability of materials that can be used throughout the fields: i.e. that economists and ecologists can use in assessing environmental profiles; or designers can use as a factor in material selection. This research will concentrate on defining recyclability of materials in a simple way that can be determined mathematically and that reflects the fluctuations of markets and changing recycling technologies.

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[1] The term designers refers to all decision makers who participate in the early stages of product development which includes industrial designers, engineering designers, manufacturing engineers, graphic and packaging designers.

[2] . The European Commission in preparing its proposal for the 6th Environmental Action Program also faced the same problem: "We also want to develop a better definition – feedstock is considered recycling in some Member States but as energy recovery in others- a classification is needed" [European Packaging and Waste Law no77, May 2000 p 41]

The need for determining a measurement of recyclability can be seen in material selection but also in material recovery. How much of a material can be recovered will depend on its use. But how much is recycled from what is recovered will depend on the material's recyclability. Therefore the recyclability of materials could be a useful tool in the stage of design and design for disassembly for easiest and fastest recovery of those materials that have a high recyclability.

Definitions.

In order to determine a recyclability index, recyclability is defined in this work as *the ability a used material has to regain the properties it had in its virgin state*. (Villalba 2002, 2003). With this definition, a recyclability index (R) can be determined based on the assumption that how well a material can be recycled will be reflected by how well a recycled material resembles the virgin material in its valued properties. A material that has a high recyclability index means that there is no difference between the recycled and the virgin material (first-production form): the recycled material is able to regain all the properties the material had in its virgin (first-production) form. Only these materials are truly recyclable, and their recyclability index is simply one (or 100%). A recycled material that is only able to reacquire a percentage of its original valued properties will have a recyclability index less than one. These materials, although they go through a recycling process, are not recyclable according to the definition here proposed, because the second time around they cannot be used the same as if they were in their virgin form. However, these materials with a recyclability index lower than one, can be used in other ways, usually of less responsibility than the virgin material. In other words, they can be reused.

This definition of recyclability on which the recyclability index R is based, is different from other definitions of recyclability commonly used. For example, the definition given by the EPA states: recyclability refers to products or materials that can be collected, separated or otherwise recovered from the solid waste stream for reuse, or in the manufacture or assembly or another package or product, through an established recycling program (EPA). In other words, the term recyclable is extended to all materials that can somehow be reused in some manner. It is important to make the distinction that recyclable materials as here defined are those that can be reused as if they were virgin materials. This will be especially useful to industries where the emphasis is the separation into pure materials so that they can be reprocessed and used to create new components, and not so much for reuse/remanufacturing.

To determine the recyclability index, there needs to be a mathematical comparison between the recycled material and the virgin material. For this comparison to be accurate, all the intrinsic and extrinsic factors that affect the recyclability of the material would need to be considered. However, to arrive at the recyclability index by mathematically determining how all the intrinsic and extrinsic factors interrelate, is quite an impossible task unless some assumptions are made. To simplify this task, an important assumption is made: *how well the recycled material resembles the virgin material will be reflected by how close the economic value of the recycled material is to that of the virgin material*.

This idea of giving recyclability a value deduced from its industrial value is not new (Nicolet, 1995). The importance of comparing the recyclabilities of materials as a financial index has been stressed before. A way of comparing economically different recycled materials could help determine the environmental and the economic gain of such recycling processes. Therefore the recyclability index will be a quantitative measure, a value that can be manipulated mathematically.

How recyclable a material is, can be seen as a two-step process: firstly, how a material's properties devalue through use (devaluation), and secondly, how they are regained through a recycling process (recuperation or gain-back). How much a material devalues will depend on the material's inherent properties, on the wear and tear through use, its lifetime, and many other intrinsic and extrinsic factors. All of these will be assumed to be reflected by the monetary value given to the used material, in other words, the price the recycler pays. The ability of a material to recuperate its properties via a recycling process will also depend on many intrinsic and extrinsic factors, which will also be assumed to be represented by the monetary value given to the recycled material. If what a material devalues is equal to what it recuperates, then the material is fully recyclable and has a recyclability index of 1. If there is a difference between these two values, then a recyclability index (R) can be determined.

Copper is an example of a material that has been recycled for hundreds of years. Since very early on, it was found that used copper could be remelted and used as if it were virgin copper. Used copper comes in many different forms, depending on the use it has had. The different types of copper scrap have their corresponding recycling processes, all of which return the copper the original properties it formerly had. Number one scrap (No 1 scrap) consists of clean, unalloyed, and uncoated copper clippings, punchings, bus bars, commutator segments, clean pipe, and tubing. Number two scrap (No 2 scrap) includes the above, but can contain oxidized or coated pieces, such as coated copper wire. No1 scrap is melted directly and can be brought to higher purity through fire refining. When the purity level desired is reached, the molten copper is deoxidized and cast into ingots and other shapes. No 2 scrap is first melted and cast into anodes which are then electrolytically refined.

Electrolytic refining involves dissolving the anodes electrolytically in a bath of sulfuric acid, and then electroplating them out of the solution onto stainless steel sheets. Thin sheets of copper are pulled off the stainless steel and placed between electrolytic cells for further electroplating until the desired purity is reached. Thus for both types of scrap, there are recycling processes established that will return the valued properties to the used copper. A more detailed description of the recycling processes is given in "Recycling Copper Scrap at United States Metal Refining Company" (Manzone, 1977).

Used copper is able to regain the valued properties of electrical and thermal conductivity, ductility and malleability, for example. Therefore, copper has a recyclability index of 1, which is also reflected by the monetary value. The price of virgin or first production copper is US$1.77/kg (USGS) and the price of recycled copper US$1.67/kg (USGS). This is a clear indication that copper has a high recyclability index since recycled copper can almost be sold interchangeable with copper of first production. A clear indication is that it is estimated that throughout history about 400 million tons of copper have been mined to date, and the majority of it is still in use today.

Paper is an example of a material with a low recyclability index. Paper that has gone through a recycling process does not reacquire its valued properties such as color, purity, and fiber properties. The fact that it has a low recyclability index is exemplified by the difference in price of virgin paper and post recycled paper: first production price (virgin) is $0.90/kg, and post recycled price is $0.14/kg (with no aid from recycling programs) (American Metal Market, Financial Times, 2000).

It is important to distinguish between the recyclability index of the material, and how much of the material is actually recycled. The recyclability index of a material will be determined as a parameter that, although not inherent to the material, will provide a way of characterizing the material. The recyclability index does not take into consideration what the material will be used for. In other words, although a material might have a high recyclability index, how much of it is recycled will actually depend on many other factors such as how much of the material is recuperated, its ability to be sorted from other materials, etc. Recuperation of a material will depend on the design for disassembly of the product, losses of the material, etc. For example, there are certain uses of copper such as insecticides in fungicides, where copper is not recycled because it cannot be recuperated. How much copper is recycled will depend on how much is recuperated (and not on its recyclability index). How much is recuperated in turn depends on what the copper was used for. What can be predicted, however, is that for materials that have a high recyclability index, a direct correlation will exist between the amount of the material recuperated and the amount that can be recycled. For materials with a lower recyclability index, the amount recuperated and the amount recycled differ. For example, a large percentage of recuperated paper is used for insulation, molded pulp, fuel compost, and more, and is not recycled.

As stated before, it is proposed that the recyclability index will depend on two factors: devaluation and recuperation. Devaluation will be the loss of properties of the material through use, and recuperation (or gain-back) will be the valued gained back through a recycling process.

To this end, the following variables are defined. They are summarized in table 1, and illustrated in figure 1 (Villalba et al, 2002, 2003).

V_m: the minimum value of a material (US$/kg). This is the minimum value of a material before being treated or shaped for a specific use. V_m will take into consideration the costs associated with the difficulty of making that material or its geological abundance on the earth.

V_r: the residual value of a material (US$/kg). This is the value that a given material has after its primary use and before it is recycled for its secondary use. This is the price at which the recycler buys the used material. It is assumed to have included the costs of disassembly since V_r refers to the value of the materials and not a product, which is a group of materials. Disassembly will be discussed later in a separate section.

V_p: the post-recycle value of a material (US$/kg). This is the value that a given material has after it has been recycled and is ready for its second use, before being treated or shaped for a specific use.

D: devaluation, the function describing the monetary loss of a material due to use. This will be the difference between V_m and V_r, divided by V_m to make D unitless:

$$D = \frac{V_m - V_r}{V_m} \tag{1}$$

Devaluation will be 0 when $V_m = V_r$, that is when the material does not lose any value through use. D will be 1 when V_r is 0, which will mean that the used material has no value.

G: G is the function describing how much a material is able to reacquire through the recycling process. This will be the difference between V_p and V_r, divided by V_m:

$$G = \frac{V_p - V_r}{V_m} \tag{2}$$

G is 0 when V_p is equal to V_r, which means there is no recycling process involved.

Steel has a high G and gold has a low G, and they are both recyclable (see table 3.II). In other words, a higher or lower G does not mean that for a material it is easier or harder to reacquire its properties. What is a measure of this is the difference between D and G, that is the difference between the value a material loses during use and the value it is able to regain. If the difference is small, the more recyclable a material is, and the greater the difference the less recyclable it is.

C_u: costs of use. C_u can be calculated as the difference between V_m and V_r.

$$C_u = V_m - V_r \tag{3}$$

Therefore,

$$D = \frac{C_u}{V_m} \tag{4}$$

C_r: costs of recycling. These costs will include the costs of transformation of the material **C_t**, and will also include the profit of the recycler **P**.

$$C_r = C_t + P \tag{5}$$

C_r can be calculated as the difference between V_p and V_r.

$$C_r = V_p - V_r \tag{6}$$

$$G = \frac{C_r}{V_m} \tag{7}$$

R: recyclability index. It is defined as how much of the original properties lost during use (measured by D) a material is able to reacquire (measured by G). It will be defined by the following equation:

$$R = 1 + G - D \tag{8}$$

So recyclability index is 1 when G is equal to D, that is when the value lost during use is recovered through recycling.

Substituting equations (1) and (3) for G and D, results in the following equation:

$$R = 1 + \frac{V_p - V_r}{V_m} - \frac{V_m - V_r}{V_m} = \frac{V_p}{V_m} \tag{9}$$

If the value of the recycled material is so close to the value of the material of first production, this is a clear indication that the material is able to recuperate all the properties it lost during use. Therefore R is 1.

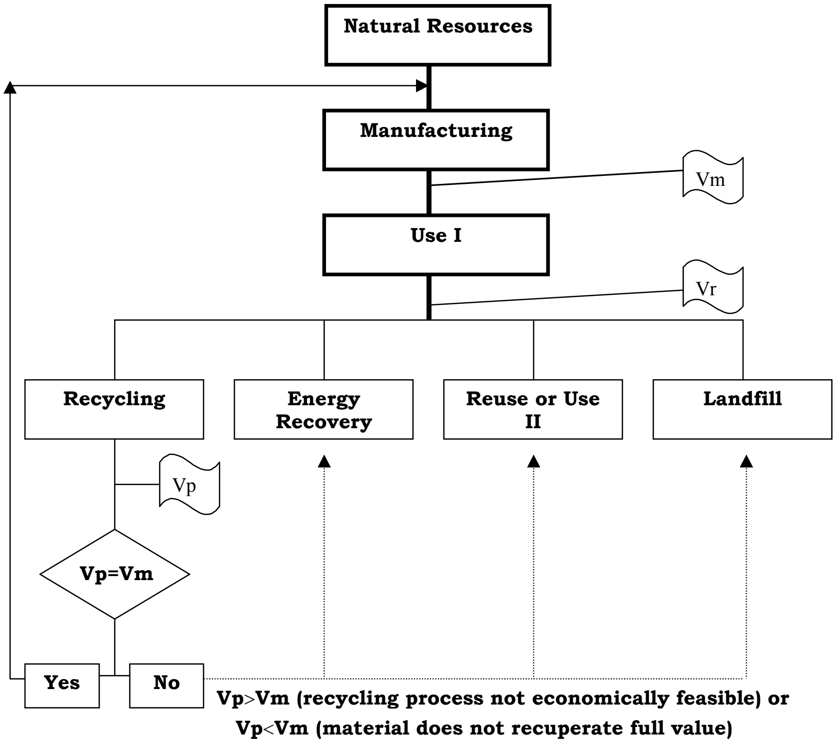

Figure 1. The life cycle of a material (Villalba, 2003).

Table 1. Summary of definitions.

Parameter	**Definition**	**Units**
V_m	Value of material in first production or virgin.	$/kg
V_r	Value of material after use	$/kg
V_p	Value of material after it is recycled	$/kg
D	Devaluation of material through use	Function
G	What a material recuperates through recycling process	Function
C_u	Costs of use	$/kg
C_r	Costs of recycling	$/kg
R	Recyclability index of a material	unitless or %

Functions.

Firstly, t is important to establish that the assumption that the recyclability index can be determined using market values is a safe assumption. This is shown by Villalba et al, (Villalba, 2002, 2003). In the above mentioned works is also explained the derivation of the recyclability index which will be skipped in this paper.

The recyclability index of a material is determined by how D (devaluation) compares to G (recuperation or gain-back), described by equation (8):

$$R = 1 + G - D$$

For materials with high recyclability indices (R is close to one), it follows then that G and D are equal to each other. A high D means that the material loses much of its value through use, and a high G means it gains much value through its recycling process. A higher or lower D does not correspond to a higher or lower recyclability index. Figure 2 shows how materials with a high recyclability index can have low or high values of D and G. What holds true for materials with R close to 1 and is exemplified by this figure is that there is little difference between G and D for a specific material. For example, steel has a D value of 0.68, and gold of 0.045, however both of them have high recyclability indices ($D_{gold} \approx G_{gold}$, and $D_{steel} \approx G_{steel}$). Figure 2 also shows how for materials with a low recyclability index, D and G are not close to each other.

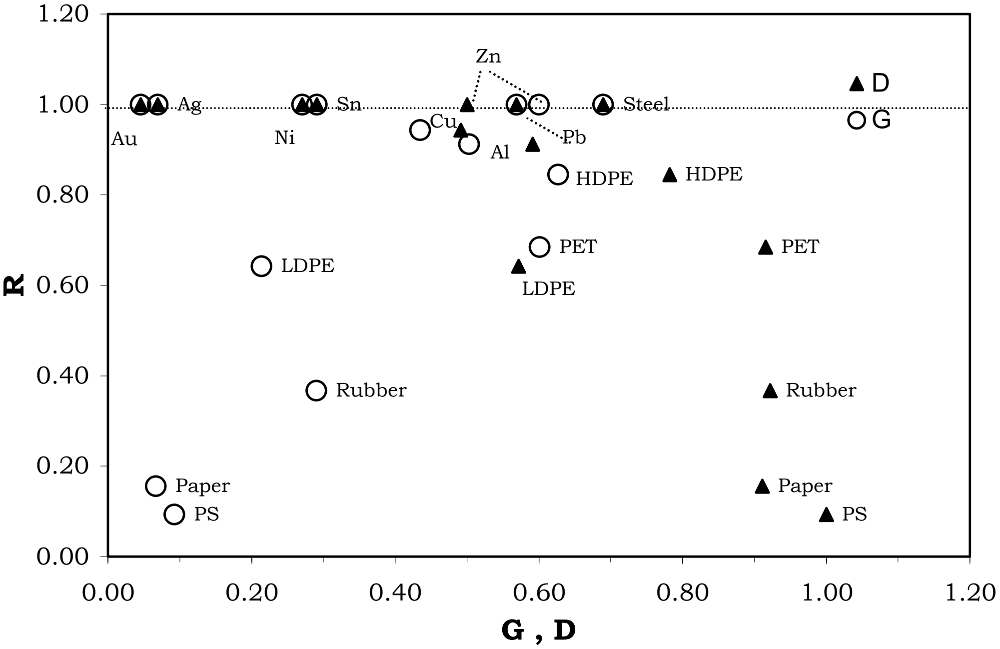

Figure 2. R versus G and D for materials with different recyclability indices (Villalba, 2003).

Devaluation of a material will be reflected by the monetary value given to the used material and how that compares to the value of the virgin material. Thus, D will be a function of both variables:

$$D = f(V_m, V_r) \tag{10}$$

Therefore, a relationship needs to be established to describe this function using materials with a high recyclability index (i.e. mostly metals). What can be suggested is that the more expensive a material is, the less it will devalue. For example, gold is such a valued material, that even through use it loses little value. Steel, on the other hand is relatively inexpensive, and has very little value after use. This is exemplified by figure 3.

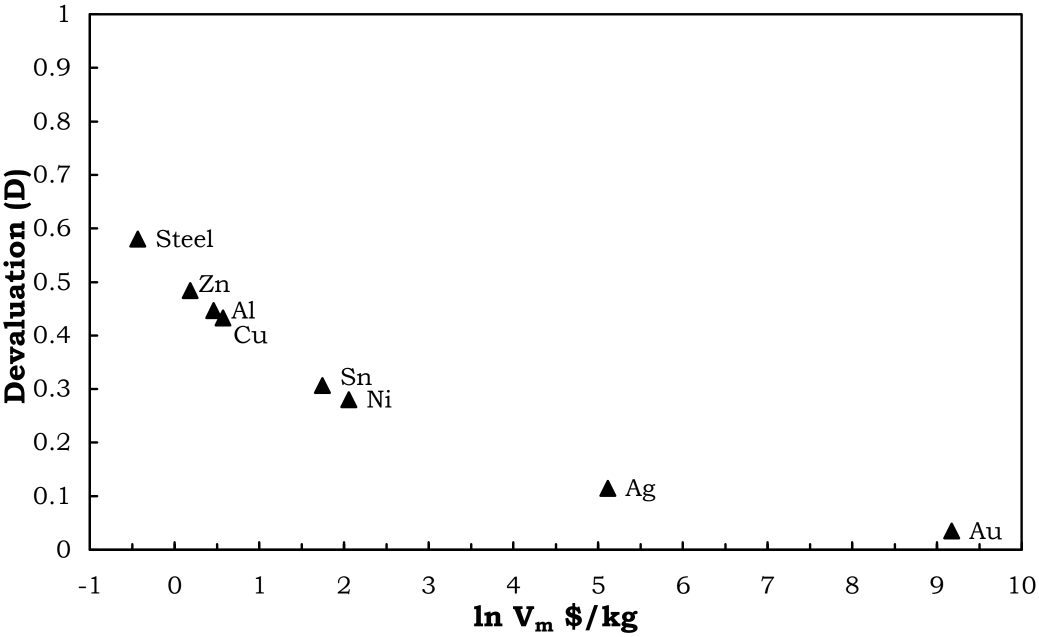

Figure 3. D versus ln V_m for materials with a high recyclability index (Villalba et al, 2002).

And is described by the equation (11):

$$D = \frac{e^{k_2}}{V_m^{(1-k_1)}} = e^{k_2} V_m^{(k_1-1)} \tag{11}$$

Where k_1 and k_2 are shown to be constants that have very little fluctuation through time (Villalba, 2002).

The same analysis used to determine devaluation can be used to determine recuperation (G). Using the assumption described earlier, the properties a material is able to recuperate through a recycling process will be reflected by the monetary value given to the recycled material and how that compares to the value of the used material. Thus, recuperation will be a function of V_p and V_r:

$$G = f(Vp, Vr) \tag{12}$$

Therefore, a relationship needs to be established to describe this function using materials with a high recyclability index. What can be suggested is that for materials where R is close to 1, those materials that retain a high value through use (such as gold or silver) have a lower G than materials that post-use have lost almost all their value (such as steel). This is exemplified in figure 4.

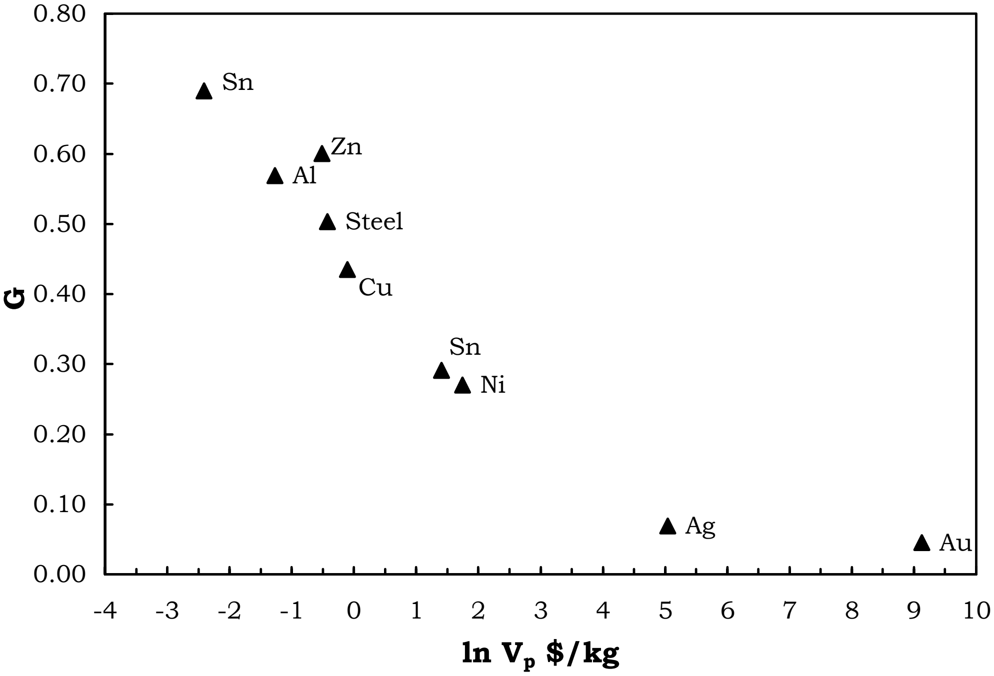

Figure 4. G versus ln V_p for materials with a high recyclability index (Villalba, 2003).

This relationship is described by the equation where k_3 and k_4 are shown to be constant through time (Villalba, 2003).

$$G = \frac{e^{k_4}}{V_p^{(1-k_3)}} = e^{k_4} V_p^{(k_3-1)} \qquad (13)$$

How intrinsic and extrinsic factors affect the recyclability index.

Up to now, a recyclability index has been estimated by economical values. However, it is important to remember that the recyclability index of materials will depend on many factors, both intrinsic and extrinsic. Factors that affect the recyclability index of materials can be classified into intrinsic factors such as the properties inherent to the material, i.e. mechanical and thermodynamic properties, and extrinsic factors such as the natural abundance of resources, price, recovery of materials, etc.

Here some of these factors will be explored, and it is attempted to establish relationships. However, how all these factors interact together to determine the recyclability index of a material is a difficult task. It is not attempted here to establish a model that explains such complex behavior, but rather to address in a generalized manner how some of these factors affect the recyclability index.

Intrinsic factors.

The intrinsic properties of the materials will play a major part in their recyclability index. Metals have been used throughout this study to illustrate the behavior of materials with a high recyclability index because their thermodynamic properties make it possible for recycling processes to render old metals like new. Some of these intrinsic properties can be quantitatively measured such as Gibbs energy, exergy, contained energy, and energy needed to recycle.

Gibbs Energy.

Gibbs energy is the driving force of a chemical reaction. A chemical reaction will take place if there is a decrease in energy of the system. Oxidation is a chemical reaction that can be used to remove impurities from a desired metal in both first and secondary (recycling) production. A thermodynamic study can be done to evaluate the feasibility of recycling processes by means of oxide formation. To decide whether this reaction is feasible, the Gibbs energy (ΔG) of the reaction needs to be determined. For example, copper is one of the more noble metals has one of the least negative ΔG^o values on the Ellingham diagram for its oxide formation (above -300 kJ(molO$_2$)$^{-1}$). Oxidation can therefore be used to remove more reactive metals from copper such as Sn, Fe, Zn or Pb (More, 1981).

On the other hand, there are other metals that have a more negative ΔG^o value and oxidation cannot be used as a means to eliminate impurities. For example, aluminum and magnesium are very reactive metals, and selective oxidation cannot be used to remove impurities from their respective scrap or ore. Other technologies are used instead, usually more time and cost consuming, such electrolytic refining in fused-salt media for aluminum recycling.

Therefore, the free energy of materials might have a bearing on their ability to be recycled. It is of interest to see how ΔG^o of oxide formation for certain metals with high recyclability behaves with parameters of the recyclability index. The following figure shows how the parameter G (which measures the value regained through recycling) compares with the standard Gibbs energy for oxide formation, which measures the ability of materials to recuperate their properties through recycling.

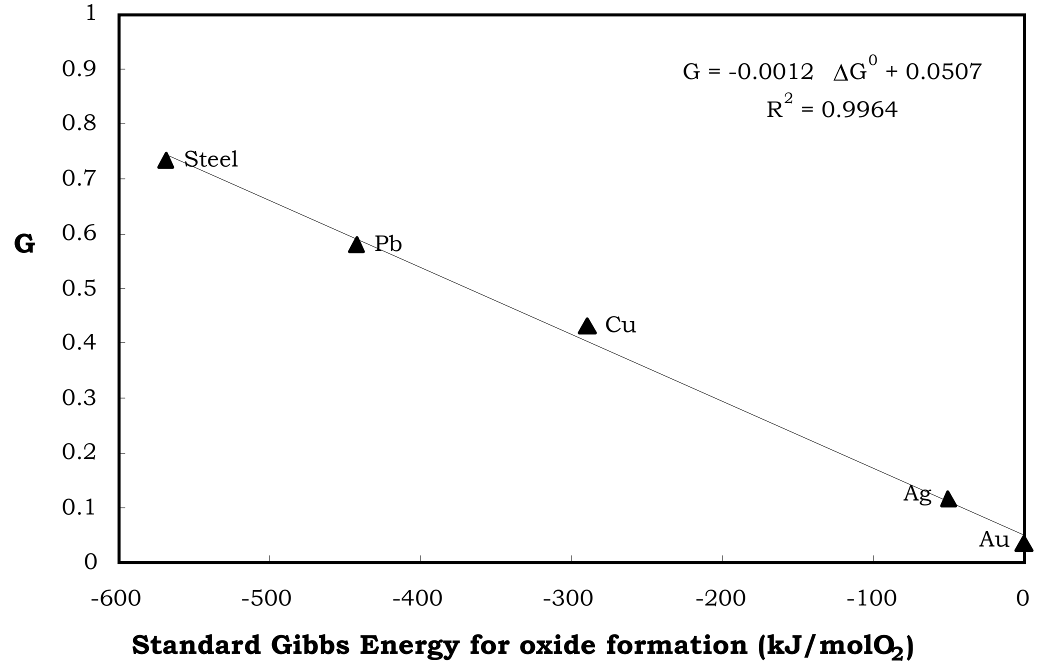

Figure 5. Relation between G and Standard Gibbs energy for oxide formation at 25°C.

There seems to be a linear relationship between recuperation (G) and ΔG^o for those metals that can be recycled by removing impurities with oxidation or reduction processes. The general trend is that the lower (or more negative) the Gibbs energy of oxide formation, the more value a metal gains through a recycling process (G) for those metals that can be recycled by oxidation or reduction processes (Au, Ag, Cu, Pb, Fe). In other words, the more reactive the metal is, the higher the costs of recycling, which are represented by the parameter G. For the other metals such as Al where other recycling processes are employed, this relationship does not hold true. This can be explained by the fact the more reactive the metal is, the higher the costs of recycling once simpler processes such as oxidation cannot be applied.

Energy needed to recycle.

The recyclability index of materials is dependent on the energy required to recycle (E_r), and how that energy compares to the energy required for first production (E_o). The ratio of energies $(E_r)/(E_o)$ will represent the energy savings obtained from recycling versus first production. Figure 6 shows G versus the energy savings ratio $(E_r)/(E_o)$, for metals that have a high recyclability index.

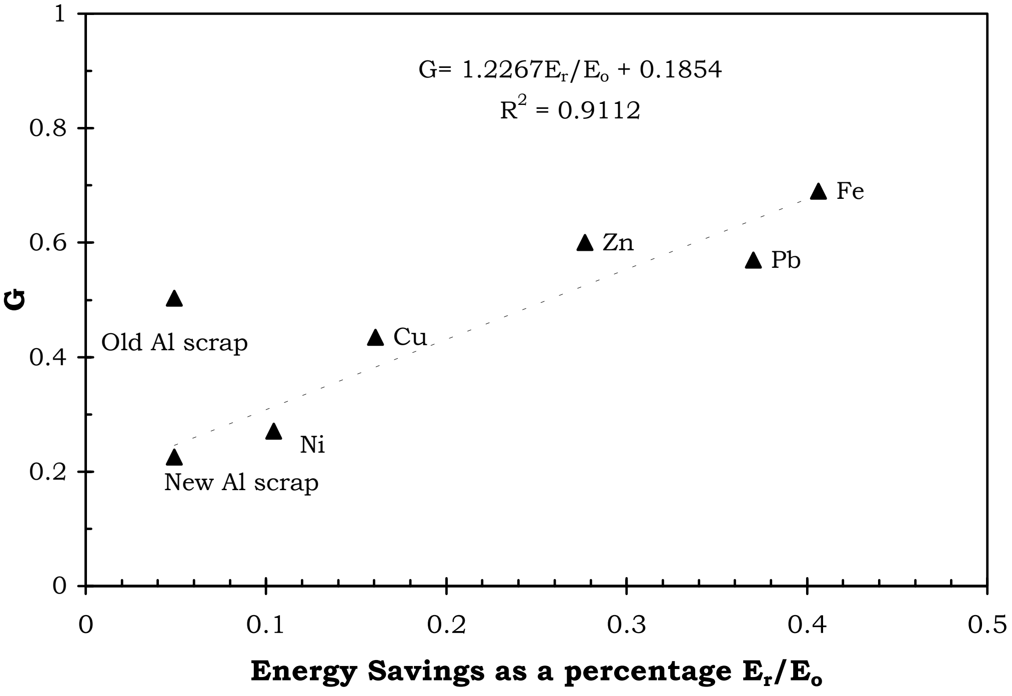

Figure 6. Relationship between G and the ratio of energy savings E_r/E_o. (Villalba, 2003)

This illustration describes how as E_r becomes much smaller than E_o ($E_r/E_o \ll 1$, the higher the energy savings due to recycling), the costs of recycling compared to the original value of the material (definition of G) decreases. In other words, the lower the energy required to recycle, the lower the costs to recycle. Aluminum recycled from old scrap is the exception to this general behavior of recyclable materials.

Al and Cu are metals that can be recycled, although Cu is recycled through a much easier process than Al. Cu is more noble, and impurities such as iron, lead, tin, nickel, zinc, etc can form oxides. On the other hand, Al is much more reactive, and oxidation cannot be used to remove the impurities. The technology available right now to recycle old scrap aluminum is electrolytic refining in fused-salt media, and this is very expensive and time consuming. There are hardly any energy savings compared to first-production aluminum. Thus, old scrap aluminum is hardly recycled. It is mixed with the primary metal (the energy associated with this process is the data point for Al given in illustration) (Kellogg, 1976).

Extrinsic Factors.

Extrinsic factors such as the market value of the material, its natural abundance or the costs of manufacturing will all play a role in how recyclable the material is. Some of these are discussed in what follows.

Scarcity of Natural Resources.

The availability of resources will play a role in their recyclability index since many of the resources are non-renewable (non-renewable resources are defined as resources that have been formed over long periods of geological time, including metals, industrial minerals, and organic materials such as fossil-fuel-derived materials used to manufacture plastics). Mineral resources cover all materials in nature that come from inorganic processes without aid of the human being. There are three types of resources: resources extracted from ore minerals such as metals; other resources such as water, air, gravel; and fossil fuels such as raw materials for plastic manufacturing or energy production. This section will pay special attention to the minerals, since it has been established that most metals have a high recyclability index.

The availability of metals will play a role in its recyclability index. The scarcer a metal is, the more enticing it is to have the technology to recycle it. Gold, for example, is a scarce metal. It loses very little value through use (only 8%), and efficient recycling of gold has existed for hundreds of years. The value a material retains through use is measured by devaluation (D), which is a parameter of the recyclability of materials. For metals, the relationship between natural abundance and D, can be analyzed and is illustrated in figure 7.

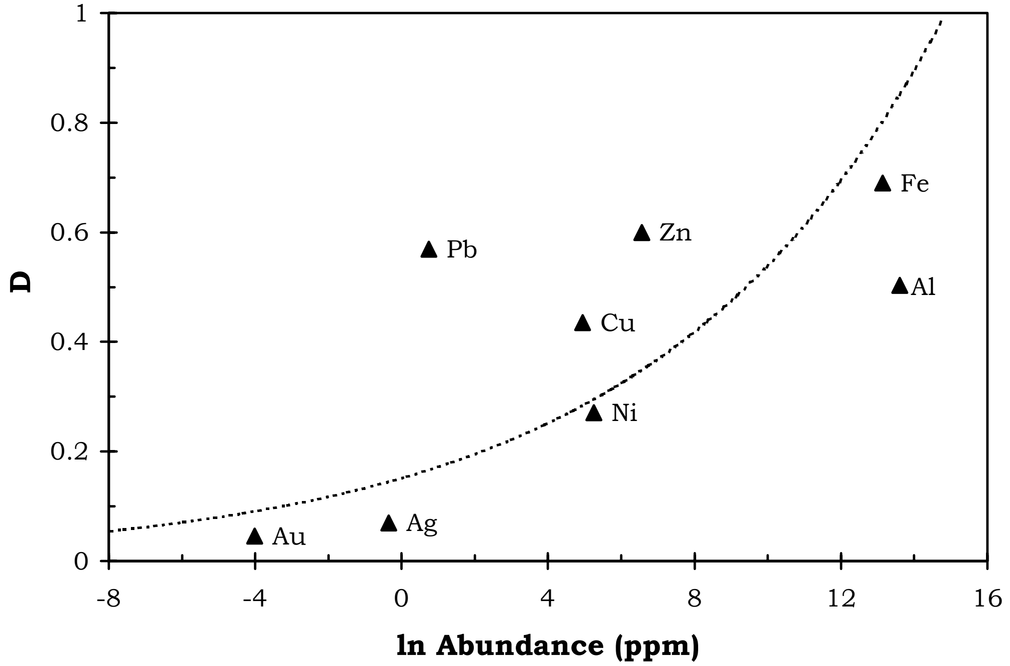

Figure 7. Relationship between D and abundance for some metals. (Villalba, 2003)

The general trend of the data plotted is that the scarcer the material is, the more value it will retain through use. The higher the abundance of a metal the more it devalues through use.

This is an important relationship to consider in the global attempt to reverse the depletion of natural resources. As resources become scarcer and scarcer ore grades become lower and lower. Materials tend to retain more value through use, and it becomes more important to recycle materials to keep up with the demand. Recycling to avoid depleting natural resources also becomes important in terms of energy savings, which was previously discussed in the introduction.

The ore grade of the mineral can also play a role in its recyclability. There is a clear link between the ore grade and the amount of energy needed to extract the metal, described by the following figure:

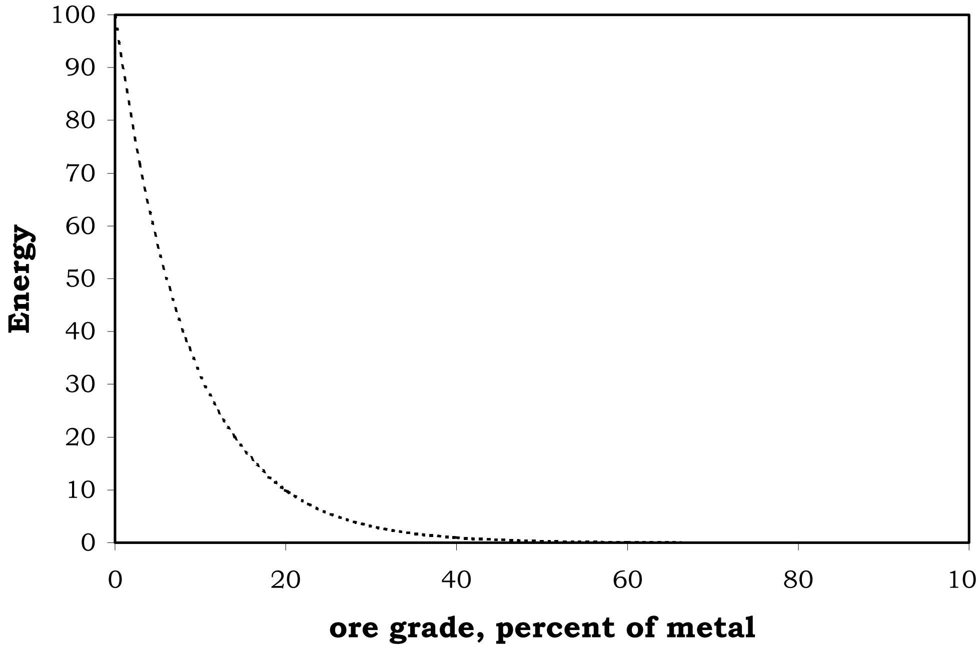

Figure 8. Expected trend between energy and ore grade (Villalba, 2003).

A more detailed correlation is given by Kellogg (1978), who also takes into account the processing of marginal resources in the future by illustrating how the ore grades of certain metals decrease and energy requirements increase.

As previously shown, as ore grades become lower and lower, the higher the energy needed to manufacture and extract there resources. Therefore the ratio of energy needed for first production versus energy needed to recycle (E_o/E_r) will be greater, making it more profitable and more attractive to recycle materials with low ore grade, and thereby increasing their recyclability index.

For energy savings data and ore grades available, the following figure is given which illustrates the expected behavior.

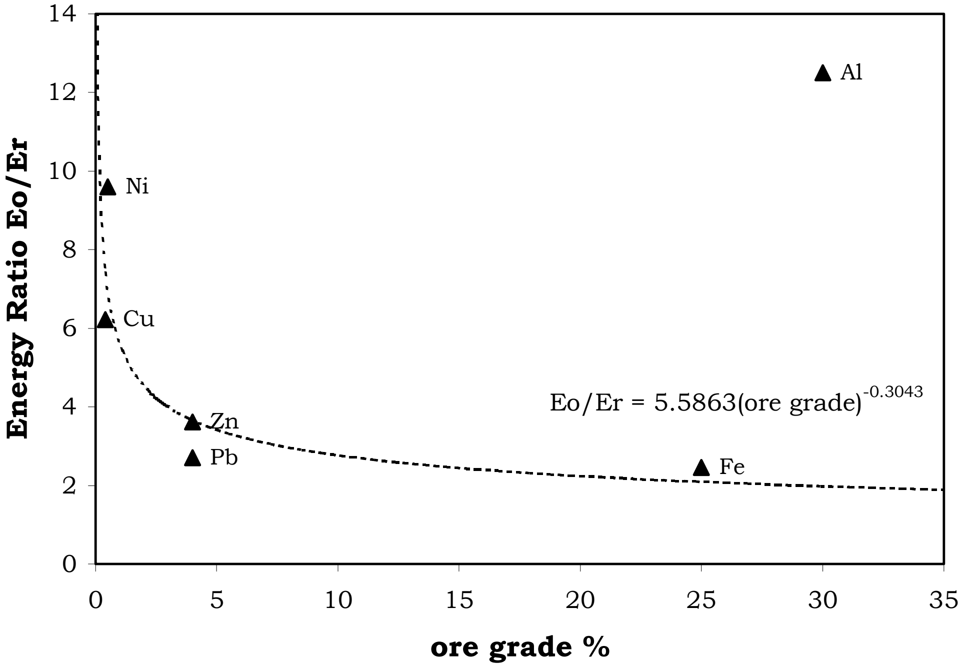

Figure 9. Relationship between the ratio E_o/E_r and ore grade (Villalba, 2003).

The expected behavior described in the earlier graph is also seen here. Aluminum, however, seems to be an exception. An explanation for this could be that the recycling process for aluminum recuperated as old scrap is more expensive and has less energy savings than aluminum recycled from new scrap, and will not have similar behavior to the rest of the metals with high recyclability index.

There are many other extrinsic factors that affect the recyclability of materials. For example:

-Recovery rate. For materials that have a high recyclability index such as metals, nearly the same amount recovered is recycled independent of time. However, the amount that is recovered does not depend on the recyclability index; rather it depends on assembly of the product or what use the material has had. The recovery rate fluctuates through time.

-Consumption. The more value a material gains through a recycling process (a higher G), the higher the secondary consumption. In other words, for materials with a high R, a high G corresponds to a high value added through the recycling process. Thus it is more lucrative to recycle these materials, and their secondary consumption is greater than for other materials that although have a high recyclability index, have a lower G.

Conclusions.

Recyclability has been defined as the ability of a material to regain all the properties it originally had through a recycling process. Using this definition, and the assumption that how recyclable a material is will be reflected by its market value, a recyclability index was determined. The recyclability index will be reflected by how the post-recycle price (V_p) of the material compares to the price of the material of first production (V_m). If the post-recycle price (V_p) is equal to the virgin or first-production price (V_m) of the material, then it has a recyclability index of 1. This is because what the material devalues (D) is able to be gained back (G) through a recycling process. As long as $D \cong G$, the magnitude of D and G do not affect the recyclability index. If V_p is not equal to V_m, then the recyclability index R is less than 1, D and G are not equal to each other, and therefore the used material once recycled cannot be used as virgin material. Materials with R less than 1 are reused, burned for energy recovery, or landfilled.

Although the recyclability index has been determined using values given by the market, it depends on both the intrinsic and extrinsic properties of the materials. Some intrinsic factors are the energy requirements of the material, the energy content; and some extrinsic factors are how well the material is recovered, its price, and other factors more difficult to measure such as people's attitudes towards recycling. For materials with a high recyclability index, some intrinsic and extrinsic factors were analyzed:

-*Intrinsic factors: Gibbs Energy*. The general trend is that the lower (or more negative) the Gibbs energy of oxide formation, the more value a metal gains through a recycling process (G) for those metals that can be recycled by oxidation or reduction processes (Au, Ag, Cu, Pb, Fe). In other words, the more reactive the metal is, the higher the costs of recycling, which are represented by the parameter G.

-*Intrinsic factors: Energy needed to recycle.* If energy needed to recycle E_r is much smaller than the energy for first production E_o ($E_r/E_o \ll 1$), the ratio C_r/V_m (that is the definition of G) decreases. In other words, the lower the energy required to recycle, the lower the costs to recycle.

-*Extrinsic factors: scarcity and ore grade.* The availability of a material will play a role in its recyclability index. The scarcer a material is, the more enticing it is to have the technology to recycle it. The higher the abundance of a metal, the more it devalues through use. As ore grades become lower and lower, the higher the energy needed to manufacture and extract there resources. Therefore the ratio energy savings E_r/E_o will be smaller, making it more profitable and more attractive to recycle these materials and increasing their recyclability index.

Discussion.

Now that a recyclability index has been defined in a way that can be measured and used as a material parameter, it can be applied to practical cases. For example, the recyclability index can be used to determine the viability of product disassembly. Disassembling is an important issue for manufacturers, designers and recyclers. Recyclers are faced with many durable products having a lifetime of 15 years (cars, small appliances, business equipment), and when they were manufactured, there had been no thought as to their disposal. Now this becomes a problem, because disassembling these products is costly. The optimum for disassembly is minimum cost and minimum time. This optimization problem is illustrated by Simon et al, which represents the uncertainty of optimizing a process in which prices and costs are constantly changing (Simon, 1992).

It is the responsibility of manufacturers and designers to design new products for recycling, remanufacturing, and reuse after disposal. The European Union has set forth take-back legislation in order to strive for sustainable development. These EU directives are specific for industry sectors such as the automobile industry, the electronics sector, and more. The responsibilities to properly dispose and recycle these products fall upon the manufacturers, who more than ever are seeking ways to meet the goals set by the EU.

For example, the EU directive on End of Life Vehicle (EU directive 2000/53/EC) came out in June 2000 (EU directive 2000/53/EC). This directive places full responsibility (economical and physical) of meeting car recycling targets on the car manufacturers. In accordance with this directive, the automotive industries are faced with having to meet the following targets: by 01/01/2006 85% weight of car must be recycled or reused, of which 5% is allowed for energy recovery, and by 01/01/2015 95% weight of car must be recycled or reused, of which 10% is allowed for energy recovery. There are presently 30 million cars a year that are being disposed (Winter, 1992). Car manufacturers are investing in research for design for disassembly and recycling in order to meet these targets. For example, in the United States, USCAR (United States Council for Automotive Research), along with the Automobile Recyclers Association and the American Plastic Council, established the Vehicle Recycling Partnership to better design to facilitate recycling.

The recyclability index of materials could be incorporated as a useful tool in the evaluation and optimization of disassembly and design for disassembly in many different industry sectors. The trend, mostly dictated by legislation, is that materials should be recycled so that once again new products can be made from those recycled materials. Therefore it becomes important to consider the recyclability index of materials, and how the materials can be optimized in order to ensure that they can be recovered.

In some cases, it is more profitable to recover a whole component than to separate it into the materials it is made up of. This is called component remanufacturing. Remanufacturing is an industrial process that restores worn products to like-new condition. In the remanufacturing process, a retired product is completely disassembled. Its reusable parts are then cleaned, refurbished, and put into inventory. Finally a new product reassembled from both old and new parts, creating a unit equal in performance and expected lifetime to the original or a currently available alternative. In contrast, a repaired or rebuilt product usually retains its identity, and only those parts that have failed or are badly worn are replaced.

Component reuse and remanufacturing, like recycling, are also a means to close the material cycle: a remanufactured component can be used as one of first manufacturing, much as a recycled material with a high recyclability index can be used as if were of first production. For example, circuit boards are a component of weigh scales that can be recovered for remanufacturing. They have a post-use value of $0.006/unit (Johnson, 1994). It is more cost effective to recover the whole component than to separate the circuit board into materials.

It is helpful to incorporate both component remanufacturing and component reuse in the life cycle of materials. Figure 10 illustrates these definitions.

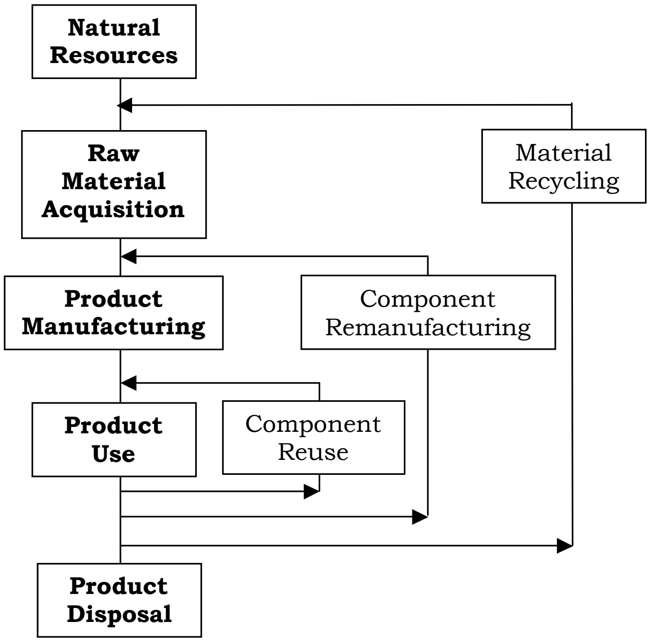

Figure 10. Life cycle: from materials to products (Villalba, 2003).

Disassembling the product in order to recover and sort all these materials is a difficult task. It is often the case that some materials are not recycled because they are not able to be recovered. Even if the materials have a high recyclability index, if they cannot be disassembled and separated, they will not be recycled. In other words, the recyclability index is a useful measurement to determine if it is physically possible to recycle the material, but in order to see how recyclable a whole product is, the feasibility of disassembling also becomes an important factor to consider.

Thus, firstly the recyclability index can be used to analyze how much of the product can be recycled if disassembled by means of a simple calculation of the weight percentage of the contained materials with high R values. Secondly, a decision factor, such as a profit-to-loss-margin ($PLM_{recycle}$) that incorporates recycling the materials contained in the product, can be determined in order to assess whether disassembly is viable. This is an important tool because it can also be used at the design stage of the product in order to ensure that at the end of its life, the product will have a high $PLM_{recycle}$ to ensure a close material cycle. (Villalba, *pending publication*)

Quantifying the recyclability of materials the way it is proposed here is extremely interesting because it contrasts the worlds of engineering possibility and economic reality. Engineers are used to suggesting many types of recycling on the basis of technical possibilities, which sometimes falter due to their disregard of economic and institutional realities. The emphasis on using realized prices of materials, virgin, used, and recycled as the foundation of recyclability indices provides unequivocal behavioral indicators.

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