THE CALCULATION OF RECYCLING RATES FOR END-OF-LIFE PRODUCTS - Theory and practice

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- Theory and practice -

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Abstract

This paper discusses the theory developed by the authors that relates product design to recycling rates based on the combination of dynamic modelling and the modelling of recycling systems. Although this theory may on first look be considered rather theoretical, it takes realistic care of the distributed properties of the product, design, life cycle, the metallurgy and physical processing, etc. This provides an insight into what factors affect the recycling rate related to design associated with a standard deviation determined by all steps within the life cycle of a car. With this knowledge a methodology is presented how recycling rates should be determined in practice based on this sound fundamental basis. Subsequently a procedural basis is provided from which the recycling rate can be calculated from an industrial experiment, for example for a recently performed recycling experiment of 1153 end-of-life vehicles, which was initiated and managed by Auto Recycling Nederland BV and executed at CometSambre in Belgium. Therefore this paper demonstrates how recycling rates can (should) be calculated from data collected from recycling experiments, referring to the various methodologies to be used in such experiments, based on the developed theory by the authors.

1. Introduction

In Europe targets have been laid down by EU legislation for the recycling rate of end-of-life vehicles to be achieved within the nearby future (Directive 2000/53/EC, 2000). These strict recycling targets are one of the driving forces for more awareness on the importance of recycling in the product's life cycle as well as for the optimization of recycling systems. Often recycling is negated by the designer, but legislation makes recycling very important. The performance of a recycling system, as well as the effect of optimizing it, can be communicated based on the achieved recycling rate. Of paramount importance in this are the definition of the recycling rate and the definition

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[1] M.A. Reuter and A. van Schaik (2004): The calculation of recycling rates for end-of-life products – Theory and practice, Proceedings of the International Auto Recycling Congress, Geneva 14-16 March 2004, 21p.

of the parameters influencing this rate as well as those affecting the realization of the recycling targets. This can only be done based on a fundamental understanding of (the dynamics of) recycling systems and the major influencing parameters. The awareness of the fact that a recycling system is a dynamic system is essential in order to describe and define the system and its parameters.
Therefore, based on the developed theory by the authors, the objective of this paper is fourfold:

- Summarise the theory developed and procedures applied by the authors to lay the link between product design and recycling rate.
- To discuss how recycling experiments should be set up with the developed theory of the authors in mind, i.e. how sampling should be performed, how data and mass balances should be reconciled within the framework of statistics, and hence to calculate a statistical sound recycling rate with a standard deviation. Also referred to is classical theory of sampling and data reconciliation.
- Discuss a recycling experiment involving 1153 cars and provide some results of this experiment to show how this theory can be applied to calculate a statistical recycling rate.
- Finally simple calculations will illustrate with the aid of a dynamic optimization model the influence of various parameters, such as lifetime, design (designers often do not take cognizance of recycling), changing metal content and material combinations of products on the definition and realization of the recycling rate of the car.

In summary this paper discusses the recycling rate as a function of numerous parameters, changing design scenarios etc. This will lead to a better understanding of the parameters affecting the recycling system and a more precise understanding of the recycling targets as imposed by EU legislation.

2. The resource cycle

The resource cycle system can be described at various levels, ranging from the global material cycles; the life cycle system of products; the recycling flow sheet; to the modelling of liberation in the shredder and optimization of the most complex metallurgical reactor. This suggests that the optimization of the resource cycle in a world in which products change rapidly is only possible if the interaction between all technological aspects of creating / using / discarding / recycling products is considered in relationship to fundamental studies including environmental control and policy. The aforementioned aspects can be summarized into the three cycles depicted by Fig. 1, symbolically showing the links between three interconnected cycles: the life cycle - the technology cycle - the resource cycle (Van Schaik and Reuter, 2004). These simultaneous interactions between the different cycles in Fig. 1 have to be orchestrated from a systems-engineering point of view, which combines knowledge of processes, production systems and unit operations with that of economics. It is therefore imperative to achieve sustainability at various system levels, from global material cycles down to plant and process equipment design and operation. Moreover the definition of the recycling rate as well as the role of various parameters in the realization of these targets can only be understood if various system levels are being regarded.

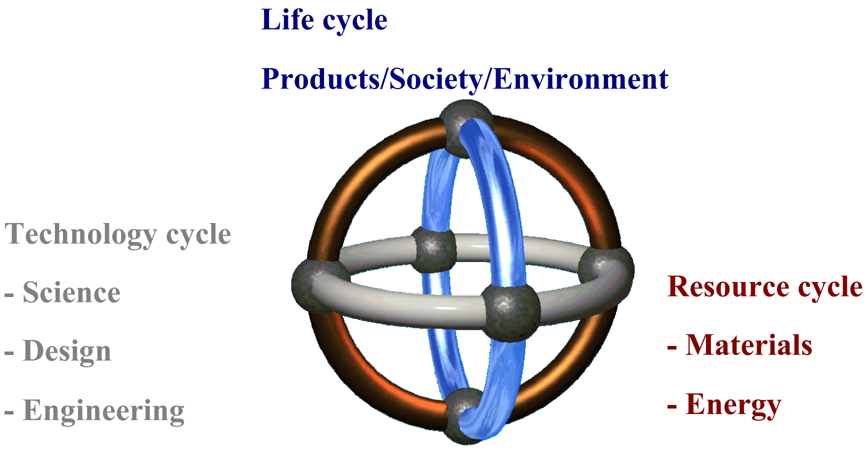


Figure 1 -Towards sustainability by linking the indicated disciplines (Van Schaik and Reuter, 2004)

3. Dynamic model of the resource cycle of passenger vehicles

In order to define the link between end-of-life products, their life time, and composition and design a dynamic model was developed for cars (Van Schaik and Reuter, 2004). The architecture of this model as depicted by Fig. 2 captures the rapidly changing design of products and their role in the material cycle, therefore predicting the input and performance of (future) recycling scenarios and the influence of design on the recycling rate. This model is the basis for the description of car recycling and shows the recycling system imbedded in the dynamic material cycle. The dynamic model predicts the behaviour of the system in time and as a function of the various involved distribution functions for the life time and composition of the car. The optimization model, describing in detail the recycling system (Van Schaik et al., 2004), predicts the recovery rate of the different materials in the car as a function of product design, efficiency of the different process steps, characteristic properties of the material flows, economics, legislation as well as the dynamic material flows through the resource system. This provides a visualization of the influence of various parameters and distributions on the recycling rate over time, therefore the basis for a more realistic definition of the recycling rate.

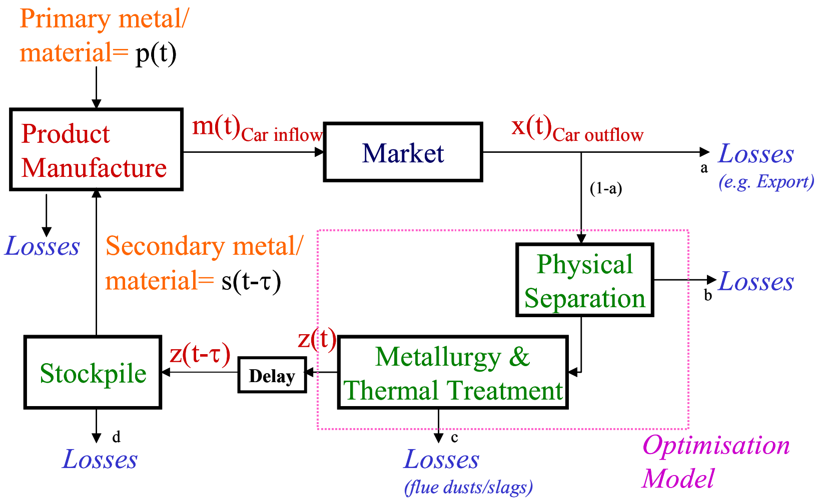


Figure 2 - The architecture of the dynamic model and scope of the optimization model to define the recycling (rate) for cars (a, b and c are mass percentages between 0 and 100) (Van Schaik and Reuter, 2004)

4. Definition of the recycling rate of passenger vehicles

The dynamic model describes and predicts the behaviour of the resource cycle system as well as the material flows within this system over time as depicted by Fig. 2. Based on this model by Van Schaik and Reuter (2004), the statistical nature of the time-varying lifetime and design of cars and the modelling of their recycling were discussed. It was demonstrated that lifetime, weight and composition of the car are changing over time and can only be described in a proper way by using various distribution functions. The average weight of the car and its materials flowing out of the use phase $x^k(t)$ (Fig. 2), which is the basis for EU legislation (Directive 2000/53/EC, 2000), is a function of the lifetime distribution of the cars, the amount of produced cars per year, combined with the changing the weight and composition distributions of the car. The definition of these distribution functions makes a more detailed formulation of the recycling rate possible and crucially determines the recycling rate. As a result the recycling rate of the car at dismantling (End-of-life) can be defined by Eq. 1, which is based on the EU definition of the recycling rate, in which $f(t_1,t_2)$ represents the lifetime distribution of the car, $g(t1,t2)$ the weight distribution and $h^k(w,mp^k,t_1)$ the distribution of the composition of the car.

Eqs. 1 and 2 show that the recycling rate cannot be represented by an average or single value as required by EU legislation, but is largely dependent on the distributed nature and therefore the standard deviations of the time-varying lifetime, weight and composition of the car. Therefore, the answer produced by the model (Eq. 1 and 2) is an average plus an associated standard deviation. In this equation the collection rate CR is determined by humans and collection systems ((1-a) in Fig. 2), whereas the recovery of each element k ((1-b) in Fig. 2) is defined among others by the (feed to) the physical recycling and metallurgical plants, therefore by $x^k(t)$.

$$\left.\begin{aligned}
\mathrm{RR(t)} &= \frac{\text{average weight of recycled/recovered material per vehicle and year}}{\text{average weight per vehicle and year}} \cdot 100\% \\
&= \frac{\sum\limits_{k=Al,steel,\,Cu,\,plastics,\,etc.} (\text{average weight of recycled/recovered component k per vehicle and year})^k}{\sum\limits_{k=Al,steel,Cu,plastics,etc.} (\text{average weight of component per vehicle and year})^k} \cdot 100\% \\
&= \frac{CR \cdot \left(\dfrac{\sum\limits_{k=Al,steel,\,Cu,\,plastics,\,etc.} x^k(t) \cdot \mathrm{Recovery}(x^k(t))^k}{N(t)} \right)}{\left(\dfrac{\sum\limits_{k=Al,steel,Cu,plastics,etc.} x^k(t)}{N(t)} \right)} \cdot 100\% \\
&\text{where } N(t) = \int\limits_{t_2=t}^{t+\Delta t} \int\limits_{t_1=0}^{YP} C(t_1) \cdot f(t_1,t_2) \cdot dt_1 \cdot dt_2
\end{aligned}\right\} \qquad \text{(Eq. 1)}$$

The average weight and composition of the car at dismantling *x*^{i}*(t)* (see Fig. 2 and Eq. 1) is described by Eq. 2.

$$\left.\begin{aligned}
x^k(t) &= \int\limits_{t_2=t}^{t+\Delta t} \int\limits_{t_1=0}^{\mathrm{YP}} \int\limits_{w_1}^{w_2} \int\limits_{mp_1^k}^{mp_2^k} C(t_1) \cdot mp^k \cdot h^k(w, mp^k, t_1) \cdot g(t_1, w) \cdot f(t_1, t_2) \cdot dmp^k \cdot dw \cdot dt_1 \cdot dt_2 \\
\text{where} \quad & \sum_{k=Al,steel,Cu,plastics,etc.} \int\limits_{mp_1^k}^{mp_2^k} mp^k \cdot h^k(w, mp^k, t_1) \cdot dmp^k = 100
\end{aligned}\right\} \qquad \text{(Eq. 2)}$$

The recovery will obviously be different for the various elements in the car due differences in liberation of the materials (strongly related to design), difference in separation efficiencies and thermodynamic properties and complex interactions between the materials as discussed by Reuter et al. (2003b). The modelling of recycling systems in order to investigate the various parameters determining the recovery rate for the various elements/materials present in the car will be discussed below.

5. Optimization of the recycling network system for end-of-life vehicles

The recycling system for end-of-life vehicles consists of a complex network of interconnected processes (each with their own recoveries, products, residues, etc.) and material and energy streams (Van Schaik *et al.*, 2004). In order to not only define the recycling rate as a dynamic function of distributed parameters (Eq. 1 and 2) the parameters determining the recovery rate for each of the materials have to be fully understood. This is only possible if recycling systems are defined more fundamentally than is the case at present. This requires sound technological knowledge on the behaviour of materials and processes within the recycling flow sheet, also in relation to the changing design of the product (and its distributed properties). This will assist in ensuring a sustainable development of our society, in which products have to comply with the recycling targets as imposed by EU legislation (Directive 2000/53/EC, 2000). The continuously changing design of the car and the application of new material combinations raise questions on the influence of car design, materials applied and their mutual interactions on the recyclability of the car in view of the EU directive on the recycling of passenger vehicles. Recycling is directly linked to the time-varying design of the product and its 'mineralogy' (material combinations and connections) as shown by Van Schaik et al., 2004. It is known from the interrelation between recovery and grade of physical separation methods for scrap, that it is impossible to obtain simultaneously a high recovery and a high grade, for a certain material stream. Increasing the recovery of a certain material will simultaneously lead to an increased amount of unwanted elements in the recovered stream, since separation processes are not perfectly selective. The combination of materials and in particular the way they are connected in product design will affect the degree of liberation, the composition of the material streams after shredding, the amount as well as the composition of the non-liberated particles and the quality of the material streams after mechanical separation, being the feed to metallurgical processing. The development of products (such as passenger vehicles) that bring together metals that are not linked in the natural resource systems (Fig. 3) has increased the complexity of recycling pyrometallurgy (Reuter et al., 2003a). As a consequence, many of these materials are not completely compatible with current processes in the metals production network, which was developed for the processing of primary natural resources, optimized for the processing not only of the primary metal but also for all mineralogical associated minor valuable and harmful elements. The formation of complex residue streams or undesired harmful emissions inhibits therefore the processing and recovery of those products at their end-of-life. Therefore mineralogy and liberation will affect the possibilities of material recovery and the recycling rate of the product. Product designers, physical liberation and separation plants, waste processors and metal producers must cooperate to realize optimal metal/material recovery in designing and recycling consumer products. This ensures that each created stream has a destination.

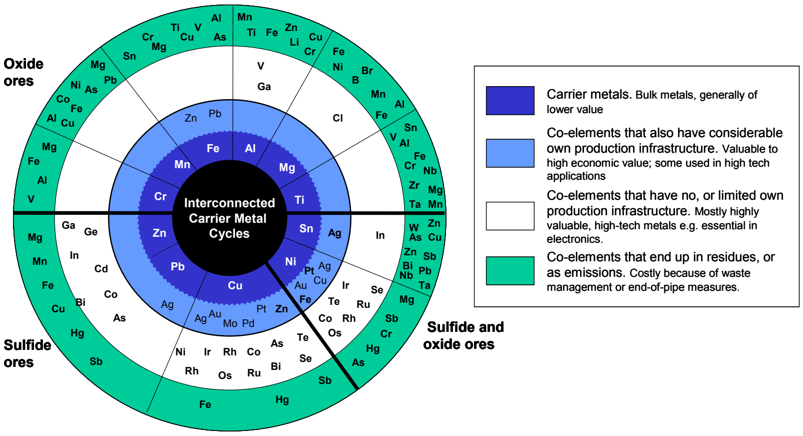


Figure 3 -Linkages of metals as found in natural resources – map to sustainable recycling of metals (legend top to bottom equivalent to rings from the inside to the outside) (Reuter et al., 2003a)

These ideas are captured by a systems engineering tool for the optimization of the recycling of end-of-life vehicles (ELV's) as discussed by Van Schaik et al. (2004). This is based on a simplified recycling flow sheet (see Fig. 4), which calculates the recovery rate for the car as a function of process efficiency and both the particle size reduction as well as the liberation of the materials as modelling parameters linking product design and final metal and material recovery, therefore, recycling rate.

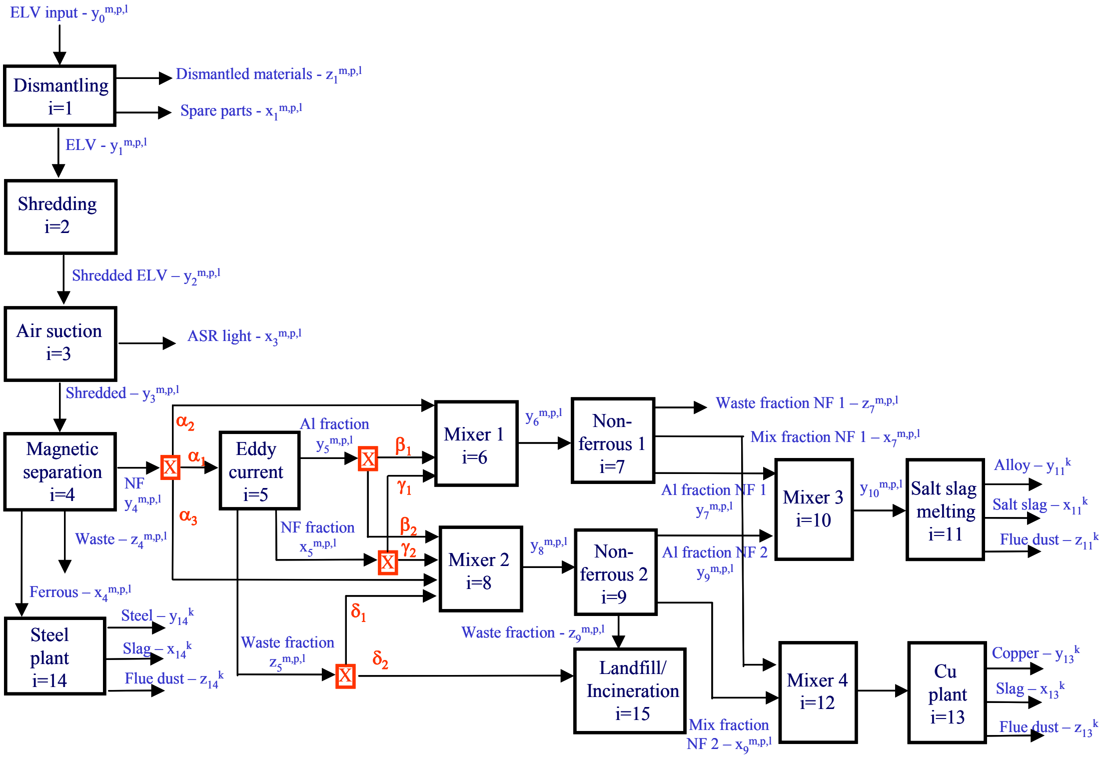


Figure 4 - Simplified generalized flow sheet for recycling ELV's, with m = A – Al wrought based mineral, B - Al cast based mineral, C - remainder based mineral, D - steel based mineral, E - copper based mineral; k = elements Al wrought, Al cast, rest, steel, Cu; particle size class p = 1 to 5; liberation class l = 1 to 5; i=plants, unit operations, transport, etc., with i = 1 to n; and α, β, γ and δ structural parameters (Van Schaik et al., 2004).

6. Practical procedures for the performing of large scale industrial recycling experiments

Recently a large scale industrial recycling test has been carried out in which 1153 end-of-life vehicles have been shredded and processed using Post Shredding Technology (PST) processes. The shredding and PST trial was initiated by Auto Recycling Nederland BV, whereas the test was carried out at Comet Sambre, a shredder and PST plant in Châtelet, Belgium. One of the objectives of this shredding and PST trial was to determine the recycling rate of cars, which can be achieved using state-of-the-art recycling technology as available at the Comet Sambre shredding and PST plant. The simplified flow sheet of Comet Sambre is given in Figure 5 and forms the basis for calculating the recycling rate.

Eq. 1 states that the recycling rate of the car is determined by the recovery of each of the materials present in the car. Therefore during a recycling experiment the mass flows within the plant and their composition must be measured and the associated statistics/distribution of the data to be able to properly estimate a statistically accurate recycling rate. This section will discuss the procedure by referring to sample size, sample weighing and the sampling procedure.

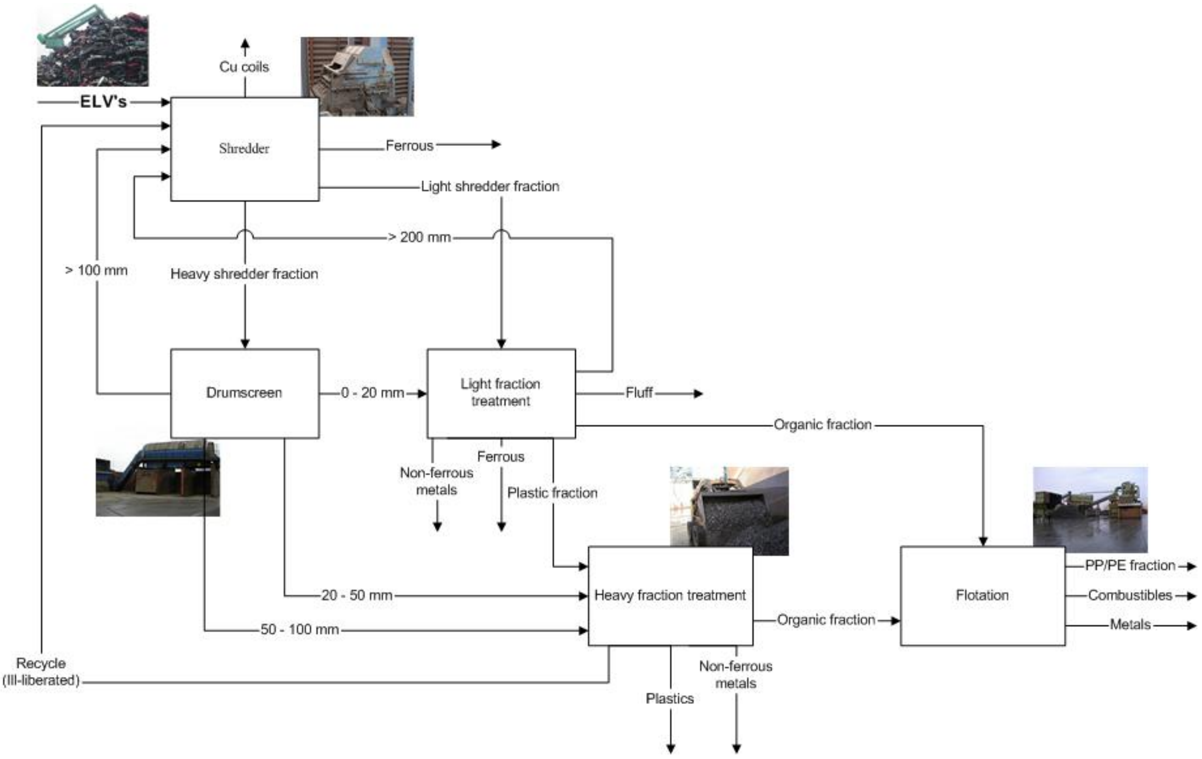


Figure 5 - Simplified flow sheet of shredding and PST trial

Calculation of required batch size of ELV's and sampling for analyses

It can easily be understood that the weight and composition of the ELV's being the input of the shredding and PST trial are all different and therefore the population of ELV's selected determine the statistics guiding the shredding and PST trial and its achieved mass balance and recycling rate. The sampling statistics are defined by Gy's formula (Pitard, 1993) relating the sample size of a stream to the accuracy (or standard deviation) of the data to be measured. The input batch size of ELV's to the shredding and PST trial is of crucial importance in the accuracy and therefore statistics of the mass balance, material analyses and the calculation of the recycling rate. Based on Gy's formula (see Eq. 3) the required sampling size for the input and all output fractions can be calculated. The calculation of the sampling size is based on the smallest compound to be measured within the output streams (e.g. 0.25% Cu in the steel stream). This approach is required due to the diverse properties of typical recycling materials as can be seen from Fig. 6. The influence of dismantling spare parts could be determined accurately based on the data collected from the shredding of the total car as well as following ARN dismantling procedures. From this it is for example possible to prove whether dismantling has a positive effect on the shredding and subsequent operations in view of EU recycling targets.

$$s^2 = \left(\frac{1}{M_{Sample}} - \frac{1}{M_{Total\ sample}}\right) \cdot f \cdot \rho \cdot \left(\frac{1}{a_C} - 2\right) \cdot d_C^3 + 0.25 \cdot d_{-95\%}^3$$

where

s	maximum tolerated error of standard deviation (-)
f	shape factor (-)
ρ	density (g/cm^3)
a_C	critical constant to be determined (0-1)
d_C	particle size at a_C (cm)
$d_{-95\%}$	particle size at which 95% lie below (cm)
M_{Sample}	Mass of sample to be taken from total (g)
$M_{Total\ Sample}$	Mass total mass of sample (g)

Simplifies to the equation below under the conditions of the experiment

$$s^2 = \left(\frac{1}{M_{Sample}}\right) \cdot f \cdot \rho \cdot \left(\frac{1}{a_C} - 2\right) \cdot d_C^3 \qquad \text{(Eq. 3)}$$

Figure 6 - Diverse properties of recycling materials

Mass balancing

Mass balances of plants based on measured data mostly do not close due to inevitable weighing and sampling errors, as is also the case for the shredding and PST trial as discussed here. Data reconciliation is a technique by which the mass balance can be closed by adjusting the process data such as mass flows and analyses within their sampling accuracy. By making use of data reconciliation, the error in the mass balance is assigned to the various measurements and the adjusted data should give a more consistent representation of the actual process. Therefore, data reconciliation can also be used to verify the quality of the measured data, to calculate poor data, as well as to estimate unknown data. There are several methods for data reconciliation described in literature (Ververka and Madron, 1997). All methods are based on the principle of minimisation of the adjustments to the experimental data while simultaneously closing the mass balance as defined by Eq. 4 and Table 1.

$$\left.\begin{aligned} & J(Y) = \sum_i J_i(Y) \\ & J_i(Y) = \left(\frac{M_i - \overline{M_i}}{\sigma_i \cdot M_i} \right)^2 + \sum_k \left(\frac{f_{ik} - \overline{f_{ik}}}{\sigma_{ik} \cdot f_{ik}} \right)^2 \end{aligned}\right\} \qquad \text{(Eq. 4)}$$

Table 1 - Symbols in the objective function of the data reconciliation model

Measured magnitudes	Errors	Adjusted magnitudes
M_i, f_{ik}	σ_i, σ_{ik}	$\overline{M}_i, \overline{f}_{ik}$
Where		
$M_i, \overline{M_i}$	mass of stream i (kg)	
$f_{ik}, \overline{f}_{ik}$	fraction of component k (steel, aluminium, plastic, rubber, etc.) in stream i	
σ_i	estimated measurement error in M_i (‘variance’)	
σ_{ik}	estimated measurement error in f_{ik} (‘variance’)	

Adjustments made to the experimental data do not have total freedom within the range in which variation is possible. Certain restrictions apply to the freedom of the adjustments:

- Material conservation constraints for which the delta is zero applied to all elements, compounds and total mass (Symbols in the objective function of the data reconciliation model)
  - ➢ $\sum_i \overline{M}_i = 0$ and $\sum_i \overline{M}_i \cdot \overline{f}_{ik} = 0$
- Data integrity constraints (e.g. the sum of component fractions in a stream should always be 1)
  - ➢ $\sum_k f_{ik} = 1$
- User defined constraints

<u>Weighing, sampling and analyses of material flows</u>

Characterisation of input (1153 ELV’s)

It is illustrated by Eq. 1 and 2 that the recycling rate of passenger vehicles is determined by various statistically distributed parameters, such as the design of the car. Therefore the calculation of the recycling rate based on this large scale industrial trial should take cognisance of the statistical nature of the recycling rate. The statistics of the recycling rate are determined by the standard deviation of the measured data (weight and composition of material flows), as well as by the statistics of the input of the test. Each of the 1153 end-of-life vehicles was weighted before the trial revealing the weight distribution. Moreover the vehicles were visually inspected before the trial to make an inventory of missing parts. The composition of the cars (as well as of the missing parts) is known from ARN databases. The input of the test is therefore very well defined, which is crucial to derive an accurate mass balance, with its corresponding statistics. Fig. 7 shows the weight distribution of the 1153 cars being the input of the test.

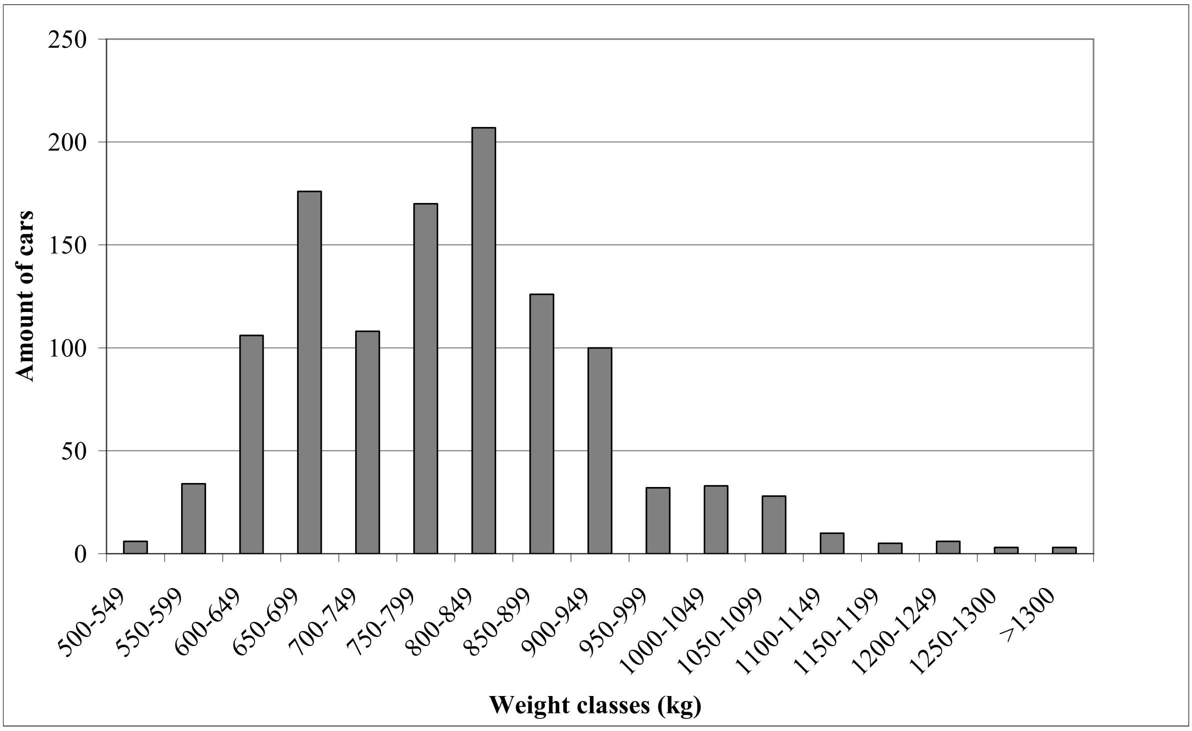


Figure 7 - Weight distribution of the 1153 ELV's

Weighing of all streams

Data collection on all material flows makes it possible not only to set up a mass balance over the total flow sheet, but also over the 5 different process steps as can be seen from Fig. 5 (shredding, drum screen, Light Fraction treatment, Heavy Fraction treatment and Flotation). If a proper and statistically sound mass balance is to be set up, data cannot be simply collected on the output of the total flow sheet as has been the case in practice up till now for similar (although smaller) tests. It must be measured over all steps i.e. on the input, intermediate and output streams, in order to increase the amount of data available for data reconciliation, which increases the accuracy of the mass balance and its statistics.

Sampling

Gy's formula is used to calculate the required sample size for each individual material flow in order to carry out reliable analyses, based on particle size, critical component to be analysed, shape factor of the particles etc. as defined by Eq. 3. This equation dictates the weight of each sample.

Analyses of material flows

The calculation of the mass balance by data reconciliation (Eq. 4) and recycling rate not only requires data on the total weight of the material flows within the plant, but also the composition of each stream. A large body of data renders the mass balance more accurate and makes it possible to calculate the recovery for each of the different materials over the various process steps. Eq. 1 indicates that the recycling rate of the car is determined by the recovery of each of the materials and the statistics are affected by the standard deviation on the composition of the various material flows.

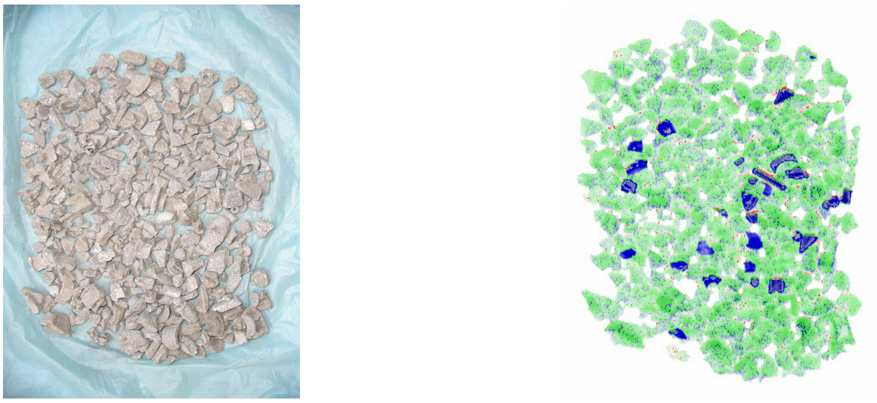
The samples of all the material flows were analysed to determine their material composition by the use of hand sorting into fractions of the numerous materials composing the car. The composition is consistently measured over all streams, so that a mass balance can be set up for all (main) materials composing the car. Since hand sorting is not selective enough for some materials, additional separation is performed on the relevant streams. Density separation (heavy medium sink-float) has been carried on aluminium/magnesium mixtures produced by hand sorting, since it is very difficult to make a visual distinction between these two metals. The density separation is also applied to analyse the organic fractions. The material flows with a very small particle size distribution (between 0-4 mm) have been analysed using XRF-analysis (X-ray Fluorescence).

Quality control by means of other equipment

The quality of hand sorting was also controlled by making Dual X-ray transmission scans of the hand sorted materials. XRT images were made from both the sampled stream from the plant as well as the numerous material fractions after hand sorting in order to control the material content of the sorted fractions, whereas the XRT scans of the unsorted sample gives an indication of the composition of the stream before analyses. Figs. 8 to 10 show the normal pictures and XRT images of three different fractions viz. plastic fraction (Fig. 8), Al/Mg fraction (Fig. 9) and an un-liberated fraction (Fig. 10) all three after hand sorting. The XRT image of the plastic fraction (Fig. 8(b)) shows that the plastic fraction is free of other materials, but contains flame-retardant plastics (dark blue) as well as PVC (pink). Fig. 9(a) shows a picture of an Al/Mg fraction after hand sorting. The XRT scan of Fig. 9(b) makes clear that the Al/Mg fraction still contains some other (heavy) metals (dark blue particles). Based on the knowledge that the ferrous components have been removed by a magnet during hand sorting; the dark blue colour in the XRT scan (see Fig. 9(a)) suggests that the Al/Mg fraction is contaminated with stainless steel (stainless steel can have a similar appearance as wrought aluminium). This is once again evidence of poor design since not all materials were liberated during shredding. Fig. 10(a) shows a picture of un-liberated particles. The XRT scan of this material (Fig. 10(b)) shows that the particles contain more than one material, e.g. the rubbers contain a core of steel, whereas some of the plastics contain steel bolts. It becomes clear from Fig. 10(a) and (b) that this can never be separated by (hand) sorting. However during hand sorting estimation is made of the composition of the ill-liberated particles in combination with the XRT images of the material.

(a) (b)

Figure 8 - Plastic fraction after hand sorting; (a) normal picture; (b) XRT image



(a) (b)

Figure 9 - Al/Mg fraction after hand sorting; (a) normal picture; (b) XRT image

(a) (b)

Figure 10 - Un-liberated fraction after hand sorting; (a) normal picture; (b) XRT image

Calculation of mass balance on such an experiment

The calculation of the recycling rate was carried out in various steps. Each of the different steps required are discussed below in separate sections. Due to confidentiality only selected data of the experiment is provided for illustration of the methodology.

Data reconciliation
Mass balances were set up over the in- and output of the 5 different process steps within the shredding and PST trial (see Fig. 5), as well as over the total flow sheet. Data reconciliation was at first carried out over each of the five 'black boxes' in order to derive a closed mass balance on total mass flow as well as for the various components present in the car over each black box based on the measured data. The standard deviation used for the data reconciliation is determined for each stream and analysis individually based on the accuracy of the weighing; sampling and analyses (see Table 2 for the Heavy fraction treatment).

Table 2 - Original data, standard deviation and adjusted data on mass flows and composition on the Heavy fraction treatment (based on the mass balance per process step)

Heavy fraction treatment		M_i (kg)	$\overline{M_i}$ (kg)	σ_i (%)	$f_{i\,steel}$ (-)	$\overline{f}_{i\,steel}$ (-)	$f_{i\,Al}$ (-)	$\overline{f}_{i\,Al}$ (-)	$f_{i\,plastics}$ (-)	$\overline{f}_{i\,plastics}$ (-)	$f_{i\ldots}$ (-)	$\overline{f}_{i\ldots}$ (-)	σ_{ik} (%)
Input	22	30340.0	30119.5	0.5	0.0588	0.0619	0.5100	0.4588	0.1677	0.1802	…	…	5
Output	25	2054.0	2049.0	0.5	0.7717	0.7715	0.0742	0.0744	0.0165	0.0165	…	…	5
	…	…	…	…	…	…	…	…	…	…	…	…	…
	…	…	…	...	…	…	…	…	…	…	…	…	…
	28	15080.0	15347.0	0.5	0.0051	0.0051	0.8671	0.8699	0.0138	0.0138	…	…	5

Moreover the original and adjusted weights and composition of the various flows throughout the plant as a result of data reconciliation is given in Table 2 for the Heavy fraction treatment (obviously similar Tables have been derived for the other process steps).

By comparing the original and adjusted data, the measured data (weights and composition of flows) can be verified. The standard deviation around each dataset together with the standard deviation of the input determines the statistics of the experiment. From the reconciled data of the closed mass balances split factors R_{jk} for the various materials k can be calculated for each output stream j over the different black boxes as illustrated in Table 3 for the Light fraction treatment. Once again due to confidentiality only a small selection of results is presented, however, note the components analysed for.

Table 3 - Split factors R_{jk} for the Light fraction treatment given for some components are calculated from the reconciled mass balance for the Light fraction treatment (based on the mass balance per process step)

	Light fraction treatment												
	Split factors R_{jk}												
j	**Total mass**	Steel	Al	Plastics	Zinc	Brass	SS	Cu	Rubber	Foam	Textiles	Wood	Glass
5	0.45	0.03	0.00	0.18	…	…	…	…	…	…	…	…	…
6	0.01	0.00	0.00	0.02	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…
20	0.03	0.15	0.29	0.01	…	…	…	…	…	…	…	…	…

Samples on material flows

During the test, samples were taken from each of the streams (intermediate and output) in the plant. The substantial sample sizes led to mass differences between the output of the one process step and the input of the same stream to another process step (e.g. the heavy shredder fraction coming from the shredder, which is the input of the drum screen, see Fig. 5). Therefore, the mass balance could at first only be set up over the 5 process steps individually and not over the total flow sheet. The weight of the samples and their corresponding composition have to be added to the total (reconciled) mass flows in order to achieve a correct mass balance, which is related to the input weight of the 1153 end-of-life vehicles, permitting a correct calculation of the recycling rate. The split factors of Table 3 have been applied to recalculate the mass flows within the plant including the mass and corresponding composition of the samples. Since the mass balances could not be set up initially over the total flow sheet due to the batch nature of the plant and the sample weights removed from the various streams between the different process steps, data reconciliation has to be performed to progress from the mass balance over the different process steps (Table 2 and 3), to the closing mass balance over the total flow sheet.

The data reconciliation adjusts the masses and compositions over the total flow sheet according to their accuracy in order to close the mass balance over the total flow sheet, while simultaneously the mass balances over the different process steps remain closed. The adjusted mass and material flows (composition) as a result of the data reconciliation are given in Table 4. The adjustment of the mass and material flows in order to close all mass balances will obviously lead to a slight redefinition of the split factors.

Table 4 - Original data, standard deviation and adjusted data on mass flows and composition on the total flow sheet (including sample weights) for the Light fraction treatment.

Light fraction treatment		M_i (kg)	$\overline{M_i}$ (kg)	σ_i	$f_{i\,steel}$ (-)	$\overline{f}_{i\,steel}$ (-)	$f_{i\,Al}$ (-)	$\overline{f}_{i\,Al}$ (-)	$f_{i\,plastics}$ (-)	$\overline{f}_{i\,plastics}$ (-)	$f_{i\ldots}$ (-)	$\overline{f}_{i\ldots}$ (-)	σ_{ik}
Input	1	149927.5	151755.3	0.5	0.0251	0.0228	0.0046	0.0045	0.2026	0.2176	…	…	5
	21	40277.3	40214.7	0.5	0.0228	0.0279	0.3342	0.2677	0.2538	0.2465	…	…	5
Output	5	86080.0	86135.6	0.5	0.0020	0.0019	0.0000	0.0000	0.0868	0.0895	…	…	5
	…	…	…	…	…	...	…	…	…	…	…	…	…
	20	6674.1	6674.4	0.5	0.1135	0.0968	0.4973	0.5044	0.0480	0.0480	…	…	5

Input (missing parts)

Although very limited, inevitably some parts of the cars were missing like e.g. mirrors. An inspection was carried out on each of the 1153 cars wrecks, input of the test. The cars were weighted and inspected on composition; the missing parts of each car wreck (e.g. mirrors, doors, etc.) were registered. The actual recycling rate of end-of-life vehicles based on this shredding and PST trial should be calculated on the weight of complete end-of-life vehicles (weight and corresponding composition). In order to calculate the recycling rate based on complete ELV's, the actual input weight and composition of the tests have to be recalculated to a complete ELV's including the missing parts, from which the weight and composition is known from the ARN database. Using the split factors calculated from the data reconciliation over the total flow sheet, the mass balance (for total mass flows as well as for the components) was calculated for complete ELV's to serve as the basis for the determination of the recycling rate.

Recycle streams

In the normal shredding and PST procedure streams are being recycled to the shredder in order to reduce the particle size or re-shred the un-liberated materials. As within the shredding and PST trial this was not possible from a practical point of view, some streams are present in the mass balance as output streams, which would normally find their way back to the shredder and PST plant. To be able to calculate the recycling rate properly, these recycle streams have to be included in the calculations of the mass flows. Since these streams redistribute through the plant, but once again also partially end up in their stream of origin, this can never be calculated properly just based on the derived split factors. The recalculation of the final mass balance is carried out based on data reconciliation over the total flow sheet of the trial (see Fig. 5) including the recycle streams.

When calculating the split factors based on the reconciled data for the total flow sheet, it becomes clear that the recycle streams will affect the split factors, and that these will change, making the use of split factors to calculate the total mass balance including the recycle streams in the plant inaccurate and not representative for the actual situation.

The mass balance over the total flow sheet, including sample weights and recycle streams based on the input of complete ELV's forms the basis for the calculation of the recycling rate and the determination of its statistics.

7. Theoretical calculation for the recycling rate

Van Schaik and Reuter (2004) have shown by various simulations, using the dynamic system model that the weight and composition of the car at production and dismantling, as well as the materials accumulating in the system, are determined by the different distributions and are highly dependent on changes in these, dictated by design. The simulations show the effect of the distributions for the lifetime, weight and composition on the definitions and realization of the recycling rate. Moreover the influence of the design (material combinations and connections) and hence liberation and particle size reduction on the final recovery and recycling rate was illustrated by Van Schaik et al. (2004), using the developed optimization model for recycling end-of-life vehicles. Fig. 11 illustrates the effect of both the changing distributions for the life time, weight and composition of the car as well as the effect a changing recovery rate due to changes in design and liberation on the final recycling rate in four different simulations. The lifetime, weight and composition distributions of the car were changed by varying the shape and scale of the distribution functions for the different simulations by changing the parameters of the distribution functions as indicated in the figure caption. For example, the recoveries are dependent on the available recycling technology, the efficiency of the different processes for mechanical and metallurgical recycling, the optimal arrangement of the recycling flow sheet, the liberation and combination of materials (e.g. see Fig. 10) in the car (complex design can complicate liberation) to name a few. Therefore Fig. 11 represents the changing recycling rate over time, whereas the recovery rate for each of the materials is varied over the dismantling years as a consequence of changing design, liberation, particle size distributions, and efficiency of physical and metallurgical processing. It must be mentioned that the simulations presented here in Fig. 11 do not intend to calculate the real value for the recycling rate of the car being achieved in Europe at this moment. The recovery values given in the figure captions (Fig. 11) are estimated values in order to illustrate the effect of the various distributions dictated by design combined with the collection rate and recovery of the components on the recycling of the car.

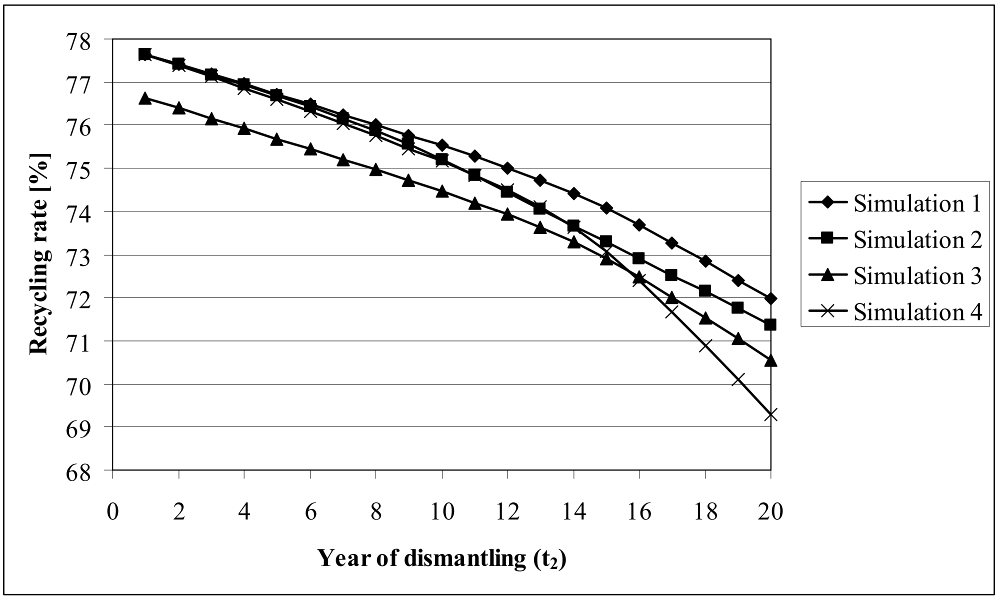


Figure 11 - Recycling rate (RR (t), Eq. 1) of the car as a function of the year of dismantling t_2 for simulation 1 to 4; Simulation 1 - Constant life time (*$f(t_1,t_2)$*); Simulation 2 - Increasing life time (*$f(t_1,t_2)$*); Simulation 3 - Increasing weight distribution $g(t_1,w)$; Simulation 4 - Changing composition $h^i(w,mp^i,t_1)$; CR=1, Recovery^{Al} =0.90 (t_2=1) to 0.81 (t_2=20), Recovery^{Steel} =0.99 (t_2=1) to 0.94 (t_2=20) , Recovery^{Copper} = 0.90 (t_2=1) to 0.85 (t_2=20) and Recovery^{Rest} = 0.10 (constant).

The results presented in Fig. 11 indicates that these complex systems can only be properly analyzed using the definitions of recycling rate based on a dynamic model, the defined distributions in combination with the detailed knowledge of the recovery of materials within the recycling system as a function of design, shredding and liberation as well as recycling efficiency, which can also be of a distributed nature. The time-varying standard deviations of the combination of all these parameters (design, recycling efficiency, etc.) determine the error margins or in other words the standard deviation of the calculated recycling rates. The range is dictated by the combination of the various distribution functions and their respective standard deviations. This theory developed by the authors (Van Schaik and Reuter, 2004; Van Schaik et al., 2004) determines how recycling rates should be calculated taking consideration of how a recycling experiment should be organized, the methodologies to be used in such experiments. This theory takes care of all the distributed properties of the product, design, life cycle, the metallurgy and physical processing, etc.

8. Practical calculation of the recycling rate from the recycling experiment

The mass balance derived from the data of the shredding and PST trial for complete ELV's over the total flow sheet, including the sample weights and taking cognisance of the recycle streams within the flow sheet forms the basis for the calculations of the recycling rate. Moreover the composition of the various (output) flows defines the quality of the output streams, which determines the possibility of the application of the produced output streams.

Depollution

The weight and composition of the 1153 ELV's, being the input of the test, have been determined based on the weighing of the car wrecks and the ARN database. The car wrecks being the input of the test have been depolluted before shredding according to legislation (Decree of 24 May 2002). The materials for depollution (battery, oil, cooling liquid, brake fluid, tires, inner tubes, windscreen washer fluid, LPG-Tanks, fuels, oil filter) were not part of the input of the test and are therefore not included in the mass balance as described above. In order to calculate the recycling rate of the complete vehicle, the recovery of the materials for depollution has to be included in the calculations.

System boundaries

The definition of the system boundaries is important for the calculation of recyclability and recoverability rates. System boundaries I and II can be defined for the determination of the recycling and recovery rate, see Fig. 12.

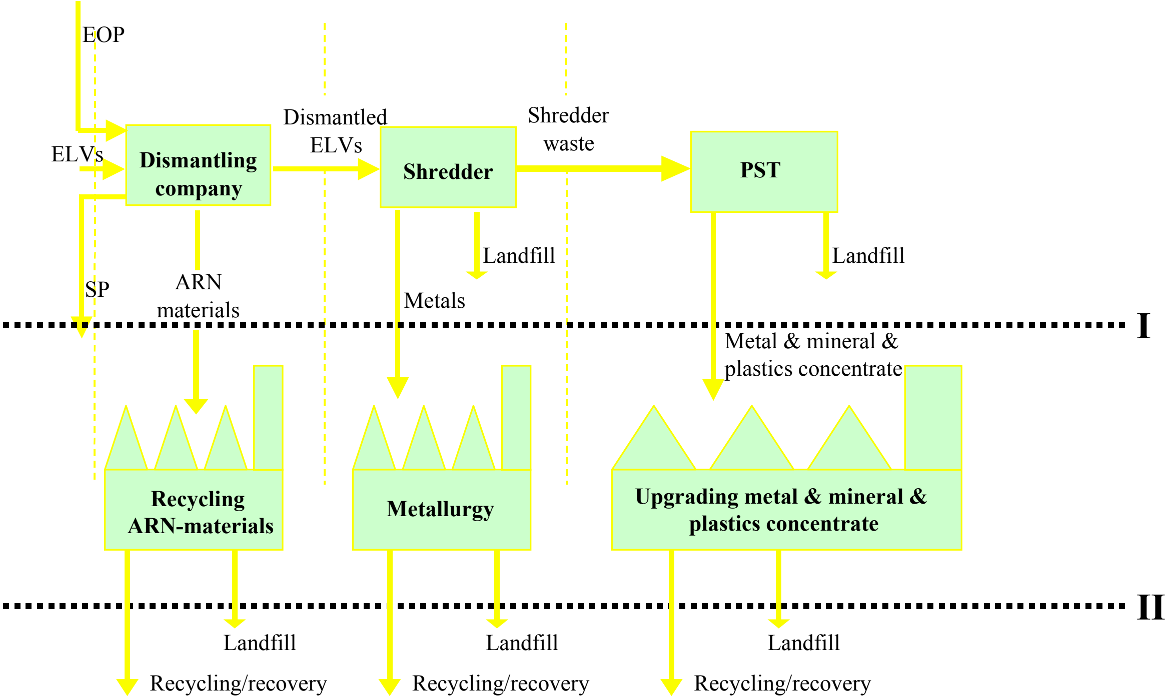


Figure 12 - ELV recycling chain with system boundaries.

System boundary I

In the calculation of recyclability and recoverability a 100% yield is assumed for the materials entering the recycling or recovery process.

System boundary II

Of critical importance to reach recycling targets set by legislation is the quality control of recycling intermediate products created during shredding and physical separation, which ensures that the feed to metal producing processes permits the economic production of quality metal products. Therefore for each of the recycling and recovery processes a correction should be made to compensate for losses in the process for:

- The recoveries for the recycling of C1 materials and tyres based on data of the ARN recycling companies.
- The metal recovery within metallurgical operations (e.g. aluminium melting operations, EAF, etc.) for the processing of recycling intermediate streams coming from the shredder and PST processes
- The recovery/efficiency of further processing of the mineral/plastic concentrates after the PST processes.

The calculation of the recycling/recovery rate achieved for the shredding and PST trial can hence be defined based on System boundaries I and II.

Procedure for the calculation of recycling/recovery rate and corresponding statistics

Based on the mass balance as presented and discussed above, the recycling rate of end-of-life vehicles based on the test can be calculated. Ultimately the recycling rate is determined by the possibility of the market to absorb the produced output streams (either for direct application or in metallurgical or thermal processes) and is therefore partially determined by the geographic location of the plant. The recycling rate can therefore be calculated based on the mass balance and valuable produced output streams of the plant under consideration. The recycling rate derived from this experiment would be based on the Belgium situation and market conditions.

The accuracy of recycling and recovery rate achieved is a function of the accuracy of the total experimentally determined mass balance, which is 0.3%. The quality of the output streams, which determine the possibility for selling these streams, is subject to the accuracy of the analyses of the composition of the material flows, which is 5%, as also used in Gy’s formula.

9. Conclusions

The definition of the recycling rate and the understanding of its leading parameters can only be fully captured on the basis of various models, describing different levels of the resource cycle and recycling system, thus providing information on the dynamic and distributed nature of the resource cycle as well as on the detailed modelling of the recycling system and the role of this in realizing high recycling rates.

The recycling rate is being defined as a function of the time-varying and distributed nature of the life time and design of a product. Moreover the recycling rate is determined by the recovery rate for each of the individual components/materials present in the car. The efficiency of the various unit operations within in the recycling system, together with the properties of the materials to be processed determine the recovery for each of the individual materials and therefore the maximum achievable recycling rate. This fundamental theory developed by the authors is applied to determine for a large scale industrial recycling test, how data should be measured and how mass balances should be derived in order to calculate the recycling rate of end-of-life vehicles and its corresponding statistics.

It is therefore illustrated in this paper; based on the discussion on the recycling rate of passenger vehicles, that sustainable development of modern consumer products can only be realized from a solid technological base. This is only possible if fundamental knowledge of recycling systems is combined with that of the design of the product, practical knowledge and data on recycling, economy as well as societal aspects (environment, legislation). Also the standard deviation around the mean is extremely important and affects the results. The standard deviation is determined by all the distributions within the dynamic recycling system (mass balance and composition of material streams).

This paper also suggests that a proper methodology and standard for the determination of the recycling rate can only be determined if a solid theoretical basis has been developed and adopted by the industry.

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Nomenclature

$C(t_1)$	Production rate of cars (cars/year) as a function of year of production
CR	Collection rate
$f(t_1,t_2)$	Distribution function of lifetime as a function of Years of production and dismantling
$g(t_1,w)$	Weight distribution as a function of Years of production and weight classes w
$h^k(w,mp^k,t_1)$	Mass percentage distribution as a function of weight classes w, mass percentage mp and years of production for each element k
k	Elements/components in the car (Al, steel, copper, etc.)
mp^k	Mass percentage class of element k
$m^k(t)$	Production of product (kg) for element k (Fig. 2)
$N(t)$	Amount of cars available at dismantling
$p^k(t)$	Primary product (kg) for element k
RR (t)	Recycling rate of the car at end-of-life (Eq. 1) (%)
Recovery^k	Recovery of element k

t, t_1, t_2	Year, Year of production and Year of dismantling respectively
w	Weight class
$x^k(t)$	End-of-life product (kg) for element k (Eq. 1 and 2)
$y^k(t)$	Products/cars accumulating in market/use phase for element k (Eq. 2)
YD	Year of dismantling
YP	Year of production

References

Decree of 24 May 2002, concerning the implementation of directive number 2000/53/EC of the European Parliament and of the Council of the European Union dated 18 September 2000 on end-of-life vehicles (PbEC L 269) (End-of-life Vehicles Management Decree). Bulletin of Acts of the Kingdom of the Netherlands, Publication year 2002, no. 259.

Directive 2000/53/EC of the European Parliament and of the council of 18 September 2000 on end of life vehicles, 2000. Official Journal of the European Communities L269, 21-10-2000.

Pitard, F.F., Pierre Gy's Sampling Theory and Sampling Practice by, CRC, Sec. Ed., 1993, 488p.

Reuter, M.A., Boin, U.J.M., Schaik, A. van, Verhoef, E., 2003a. Pyrometallurgy - the key to sustainable use of materials. Keynote lecture. In proceedings International Minerals Processing Congress (Keynote lecture), IMPC 2003, South Africa, Vol.1. pp. 128 – 149.

Reuter, M.A., Castro, M.B.G., Schaik, A. van, Boin, U., Remmerswaal, J.A.M., 2003b. Modelling the relationship between constructive choices in design and resource efficiency. Proceedings of the International Automobile Recycling Congress, 12-14 March 2003, Geneva, Switzerland. pp.25.

Van Schaik, A. and Reuter, M.A., 2004. The time-varying factors influencing the recycling rate of products. Resources, Conservation and Recycling (In press).

Van Schaik, A., Reuter, M.A., Heiskanen, K., 2004. The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles. Minerals Engineering (In press).

Ververka, V. and Madron, F., 1997. Material and Energy Balancing in the Process Industries, Elsevier, Amsterdam, The Netherlands.