The Optimization of End-of-Life Vehicle Recycling in the European Union

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This paper discusses how design software tools and recycling models can be linked to predict the recyclability of a car during the design phase and to provide a sound technological basis when designing for recycling. Due to the car's complex design and time-varying parameters such as lifetime, weight, and composition, recycling must be optimized on a sound technological basis in which the dynamic and statistically distributed parameters affecting the recycling rate are described and understood. This paper presents dynamic and recycling models developed to optimize the recycling of the car and to calculate recycling rates. The performance of a large-scale industrial recycling experiment based on the theory presented here is also discussed. It is indicated that without any statistics involved in the estimation of recycling-rate calculation, as well as the inclusion of the issues and theory discussed in this paper, the International Organization for Standardization norm for recycling rate calculation is really useless.

INTRODUCTION

Modern society is characterized by the extensive use of complex multi-component consumer products, of which passenger vehicles are a typical example. These goods and products are made of a wide spectrum of raw materials to meet the highest consumer, safety, and environmental requirements. At the end of their useful lives, these products are discarded and return as complex, multi-component materials that cannot directly be converted into products once more. However, E.U. legislation[1] has established targets to be achieved in the near future for the recycling rate of end-of-life vehicles (ELVs). Moreover, calculations to predict the recyclability of the car are required for the approval of cars,[2] which have to meet E.U. passenger vehicle targets.[1] These strict recycling targets have raised awareness of the importance of recycling in the product's life cycle, beginning with product design, and have necessitated the optimization of recycling systems.

To increase passenger vehicle recycling rates, the complex interconnected material cycles originating from recycled cars have to be optimized from a technological as well as economical point of view. The optimization of the resource cycle of passenger vehicles involves the interaction of various disciplines, as depicted in Figure 1 of the preceding article by M.A. Reuter and A. van Schaik: the life cycle, the technology cycle, and the resource cycle. This article links the recycling of passenger vehicles from a material and energy perspective as depicted by that figure's golden circle; recycling technology and design as represented by the grey circle; and cognizance of economy, environmental impact, and legislation as shown by the blue circle. This paper discusses the basis of a fundamental framework that links computer-aided design (CAD) software and recycling models. Further details on recycling optimization are provided in the article by M.A. Reuter and A. van Schaik.

DYNAMIC MODELING OF THE RESOURCE CYCLE

Little fundamental theory on recycling systems has been developed over the years. If CAD software is to be linked to the calculation and prediction of the recycling rate, it is imperative that a fundamental description of product (car) recycling systems is available in order to understand and optimize the resource cycle system especially.

Linking of CAD software to software that can predict and optimize the resource cycle of cars can only be realized from a solid technological understanding and model-based description of each process step. Fundamental knowledge of recycling processes, such as shredding, mechanical separation processes and metallurgy, and material characteristics of recycling (intermediate) products, such as material type and liberation, have to be combined with that of the design of the product (material combinations and connections). In order to optimize the resource cycle and maximize the recycling rate of future passenger vehicles, the parameters determining the recovery rate for each of the materials present in the multi-material ultra-light car of the future, as well as the dynamics and statistically distributed nature of the resource cycle system have to be fully understood.

In order to pre-empt these developments in the design stage, a dynamic recycling model has been developed that defines the link between end-of-life products, their composition, the maximum achievable recycling rate, and the product design.[3] The architecture of the dynamic model, depicted in Figure 2 of the article by M.A. Reuter and A. van Schaik, captures the rapidly changing design (i.e., life time, weight and composition) of the car and its role in the material cycle. The model predicts 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 the recycling system of cars and shows recycling imbedded in the dynamic resource cycle.

The dynamic model predicts the behavior of the resource cycle system in time as a function of the various involved

Figure 1. The diverse and distributed properties of recycling materials (clockwise: steel approximately 650 t. from 1,153 ELVs; copper fraction; Al/Mg/Cu/Zn fraction; plastic fraction; Al/Mg/Cu/Zn fraction; steel fraction).

distributed and time-varying parameters such as the life time, weight, and composition of the car. The combination of these factors determines the input of the recycling system in a certain moment in time. The optimization model (the "physical separation and metallurgy" and "thermal treatment" blocks in Figure 2 of the previous paper), describing in detail the processes and material flows in the recycling system, 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 (e.g., material type and liberation) economics, and legislation.[4] Figure 2 in the previous article reveals that the recycling and recovery rate for the different materials comprising the car are determined by the design captured by distribution functions and dynamic material flows through the resource cycle system.

Using the dynamic model, a definition has been derived for the calculation of recycling rate on a sound statistical basis taking into consideration the dynamic and distributed nature of the design of the car.[3] This type of approach has not previously been used in the recycling field and is a prerequisite to determine the recycling rate of future multi-material super-light car designs due to the complex distributed properties that will be created by complex designs.

The calculation method for recyclability and recoverability as defined by the International Organization for Standardization (ISO)[5] is a single-value, static approach, which is not based on detailed knowledge of end-of-life separation technology and metallurgical processing as the basis for the defined variables in the recyclability/recoverability rates. The ISO norm is not based on any theoretical knowledge of the complex behavior of recycling processes in relation to design. Therefore, it cannot supply the designer with reasonable data for type approval or information on the relation between product designs, the recovery of materials from the car, and the quality of recycling products, which ultimately determines the recycling rate.

OPTIMIZATION OF THE PASSENGER VEHICLE RECYCLING SYSTEM

The recycling of cars consists of a combination of processes ranging from de-pollution, dismantling, shredding, and physical separation to metallurgy and the processing of (in)organic components in combination with thermal treatment of recycling (intermediate) products for energy recovery. Even incineration and landfilling can be part of the end-of-life scenario. Although incineration without material or energy recovery and landfilling are not considered recycling according to legislation,[1] they are included in the recycling flowsheet in order to determine and control losses in the system as a consequence of poor design choices and/or separation. Each of these processes (except for incineration and landfill) contributes to the recycling and recovery (and also losses) of the various materials of the car, either by producing a product stream or an intermediate recycling stream, which will be the feed to subsequent separation or recovery processes. This reveals the inseparable relationship between the different processes and material flows in the recycling chain of ELVs. Therefore, recycling involves a network of interconnected processes (each with its own recoveries, products, residues, data statistics, etc.) and material and energy streams. A simplified overview of this network of interconnected processes is shown in Figure 3 of the article by M.A. Reuter and A. van Schaik. The recovery of the materials present in the car is strongly influenced by such factors as the efficiency of the different unit operations and processes within the interconnected resource cycle system as well as the optimal interconnection between the different processes in the recycling system.

Closing the material cycle requires a resource-cycle system approach in which the mutual compatibility of the successive processes of shredding, mechanical recycling, and metallurgical operations are made transparent and are optimized. Of critical importance are the quality of materials (e.g., degree of liberation) and their type and shape (particle size) at various stages in the recycling chain, which are strongly determined by product design (product mineralogy), shredding, and separation technology. Therefore, in the optimization of the resource cycle, it is essential to include the relationship between design, liberation, material quality of recycling intermediate products resulting from mechanical separation, and the metallurgical recovery.[4] In addition, economy and restrictions on environmental impact also influence the closing of the resource cycle. This has been realized in a systems-engineering tool developed by the authors. The flow and quality of the materials in the recycling system are described in this model based on:

- Distribution functions of changing car compositions as a function of design
- Mass-balance equations for each material composing the car (which also describe the structure of the flow sheet)
- Separation efficiency models for each process step and material composing the car

At the same time, the model describes the separation efficiency of the processes and the quality of the recycling (intermediate) streams as a function of particle size distribution and degree of liberation of the materials. The particle-size reduction and the degree of liberation of the materials are closely related to the design of the product (material combinations and connections) and have to be incorporated into the design for recycling strategies.

LARGE-SCALE INDUSTRIAL RECYCLING EXPERIMENT

For the practical use and reliability of the optimization and dynamic model, it is essential that useful data is available within the statistical limits of sampling and mass balancing. Until now, due to poor theoretical understanding of recycling systems, these data have not been available since recycling models were not available. Furthermore, the lack of these data within a statistical framework makes any meaningful calculation of recycling rate impossible. In fact, the ISO norm is practically of no use and legally vulnerable.

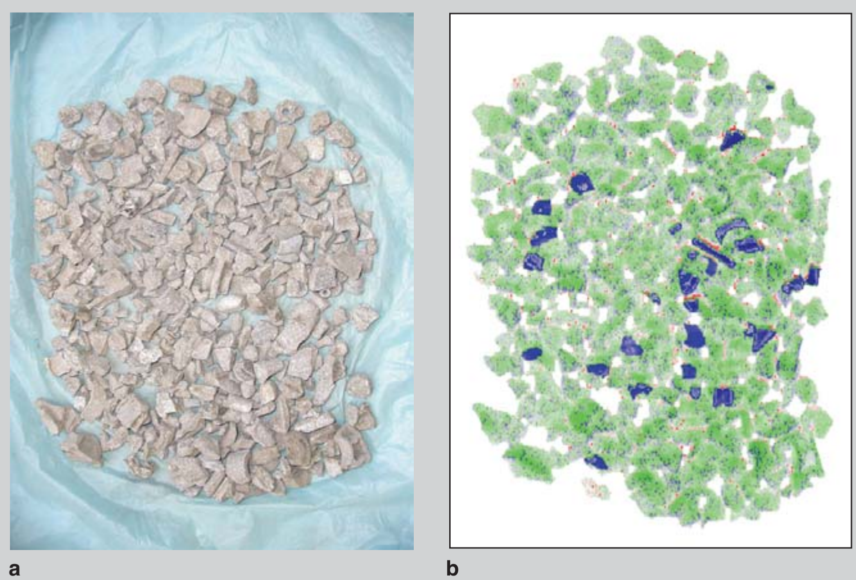
The developed theory provides a basis for proper collection of data, supported by a good mass balance based on data reconciliation and the corresponding statistics, and how this should be performed when carrying out experiments or auditing a plant. This is essential for characterizing and controlling the material and element flows in recycling plants, which is extremely important for good metal/material accounting, calculating the recycling rate on a sound statistical basis, and controlling the quality of recycling streams. Moreover, the collection of industrial data on recycling based on the best available technology is essential to predict and calculate the recyclability of passenger vehicles using the developed models.

The methodology for assessing recycling systems was demonstrated in a large-scale recycling experiment of 1,153 ELVs.[6] Experimental and industrial data on the composition of the car, the separation efficiency of the various processes, liberation and particle-size reduction in the shredder, and the quality (or grade) of the recycling (intermediate) material streams is typical information that becomes available through a good understanding of the theory of recycling.

Practical Procedures for Performing Large-Scale Industrial Recycling Experiments

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. Using the associated data, a statistically accurate recovery of each of the materials present in the car, and hence, the recycling rate can be estimated.[3]

Mass balances of plants based on measured data mostly do not close due to inevitable weighing and sampling



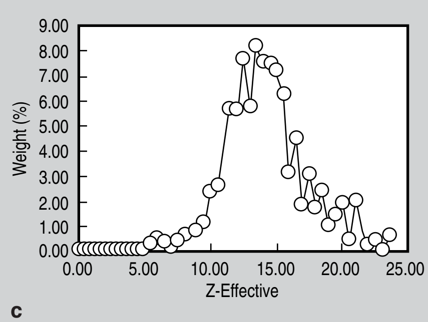


Figure 2. An Al/Mg fraction after hand sorting: (a) normal picture, (b) XRT image, (c) distribution of z-effective.

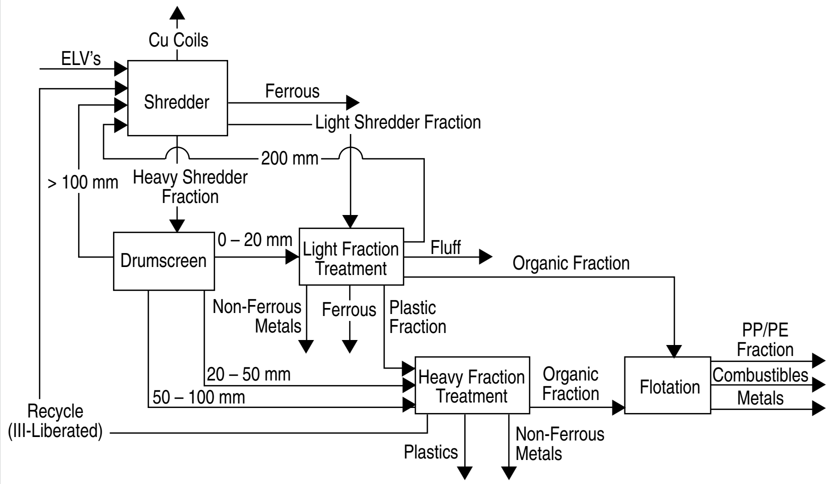


Figure 3. A simplified flow sheet of an industrial recycling plant—best available technology.[3]

errors, as is also the case for the shredding and post-shredding technology trial as discussed in this paper. Data reconciliation[7] has been applied to close total and element/compound mass balances over the plant and its unit operations. A large body of data renders the mass balance more accurate and makes it possible to calculate the recovery and grade for each of the different materials over the various process steps.

These data are used to calibrate the models in the optimization and dynamic models mentioned previously. Classical sampling theory[7] has been applied to calculate statistically correct sample sizes for analyses of the various material flows throughout the plant. The mass flows and composition of the streams were measured over all unit operations in the plant (i.e., on the input, intermediate, and output streams). This effort was undertaken to increase the amount of data available for data reconciliation and, in turn, to increase the accuracy of the mass balance and its statistics.

The recycling rate of passenger vehicles is determined by various statistically distributed parameters, such as the design of the car.[3] 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 test input. The sampling statistics as defined by Gy's formula[8] relate the sample size of a stream to the accuracy (or standard deviation) of the data to be measured. This approach is required due to the diverse properties of typical recycling materials as can be seen in Figure 1.

In this study, the samples of all the material flows were analyzed to determine their material composition by the following methods: hand sorting, sink-float tests, x-ray fluorescence analyses, and use of a steel converter for the large steel stream. The composition was consistently measured over all streams so that a mass balance could be set up for all main materials comprising the car. The quality of hand sorting was also controlled by making dual x-ray transmission (XRT) scans of the hand-sorted materials. Figure 2a shows a normal picture of a hand-sorted Al/Mg fraction. The XRT scan of Figure 2b 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 color in the XRT scan suggests that the Al/Mg fraction is contaminated with stainless steel (stainless steel can have a similar appearance as wrought aluminum). Figure 2c represents the measured z-effective (i.e., atomic number) as derived from the XRT scan. The distribution in the z-effective values measured for the material streams gives an indication of the different materials present in the stream (each with their specific z-value). Therefore, the standard deviation of the z-effective distribution can give an indication of the grade/quality of a stream (but also of the analyses) depending on the material type.

Recovery/Grade

As mentioned previously, the reconciled mass balances for both mass and element flow, the recovery (or split) factors for each element over the unit operations throughout the plant, and the quality of all (intermediate) material flows could be determined, making the calibration of models possible within the statistics of sampling and data reconciliation. The recovery factors derived from these experiments are essential for the prediction of the recycling rate when linking the recycling models to design software.

Calculation of the Recycling Rate

Based on the mass balance and its statistics, the recycling rate of ELVs based on the test could be calculated for best available technology as shown in Figure 3. The test was the first to be calculated within a statistical framework, which is crucial to proving the validity of the recycling-rate calculation. Ultimately, the recycling rate is determined by the ability of the market to absorb the produced output streams either for direct application or in metallurgical or thermal processes. It is therefore determined by the quality of the recycling (intermediate) products as well as by the geographic location of the plant. Therefore, if the recycling rate and recovery factors for each material stream are determined based on best available technology, a consistent and realistic basis is provided for the calculation and prediction of recyclability as required, for example, for the type-approval of passenger vehicles. In view of these considerations, the ISO norm for the calculation of recycling rate is questionable. Furthermore, if all parties involved in the chain of recycling cannot provide a data set within a proven statistical framework it is really dubious if any recycling calculation is watertight!

CONCLUSIONS

The complexity of the recycling system can only be fully captured and optimized on the basis of various models describing different levels of the resource cycle and recycling system. These models provide information on the

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dynamic and distributed nature of the resource cycle as well as on the detailed modeling of the recycling system and the role of design in realizing high recycling rates.

Industrial data on the performance of processes and the flow and quality of materials and components is required to link the recycling models to design software for the calculation and prediction of the recyclability of (future) multi-material ultra-light cars. Only data reported within a statistical and theoretical framework as discussed here can have a legal basis and can find their way into design software for cars. Moreover, statistics used to calculate the recycling rate based on plant data indicate that the (calculations for the) recycling rates and requirements for type-approval of cars as imposed by legislation in Europe should also have a statistical basis and are meaningless if represented by a single value, as is required at the moment.

The theory and insights presented here can give the automotive industry sufficient arguments to discuss the definition of the current recycling rate targets. The required statistics to obtain meaningful recycling data give the car designer the basis to challenge the recycling rate calculation by the ISO norm and as set out by the European Union. This challenges the recycling industry to produce good data at all times but also challenges the car industry to find solutions together with the recycling industry to ensure that the recycling rate is always calculated on the basis of best available technology and solid statistically supported data.

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