# DATA UNCERTAINTY AND CONSEQUENCES FOR DECISION MAKING

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## Abstract

*Material flow analysis (MFA) is typically used as a basis to evaluate the material efficiency and circularity of resource systems. Because MFA results are inherently uncertain, transparent and consistent methods to deal with uncertainty are required to understand the effect of data limitations on the reliability of MFA results. Here, case studies on the management of Al and Pd in Austria are used to illustrate the relationship between material flow data quality and the uncertainty of collection, recovery and recycling rates. The case study results highlight that data limitations introduce significant uncertainty concerning the actual performance of Al and Pd material management, respectively. Hence, rigorous uncertainty consideration provides, on the one hand, an incentive to improve the material flow database, and on the other hand, credible decision support while still acknowledging limited system understanding. Consequently, the transparent and consistent characterization, handling and communication of uncertainty should become standard practice in MFA.*

## Introduction

Material flow analysis (MFA) is a tool to evaluate material use patterns by quantifying stocks and flows in a temporally and geographically defined system (Brunner and Rechberger 2016). Like any other model-based decision support tool, MFA results are inherently uncertain. Due to varying data quality, limited data availability and lack of knowledge, the true value of material flows can only be approximated. However, in the past these estimates have often been presented as nominal values, which raised questions about the reliability of MFA results (cf. Laner et al. 2014). Therefore, recent efforts have been made to appropriately handle uncertainty in MFA, which encompasses 1. assessing the quality of MFA data and characterizing its uncertainty (e.g. Schwab et al. 2017; Laner et al. 2016.), 2. developing consistent methods to reconcile conflicting model inputs and propagate uncertainty (e.g. Dubois et al. 2014; Cencic and Frühwirth 2015; Džubur et al. 2017), and 3. communicating the result's uncertainty as a basis for decision making (e.g. Laner et al. 2015; Rechberger et al. 2014). These three steps in considering uncertainty in MFA are illustrated in Figure 1 together with typically used methods. In the case of the most widely used MFA software, STAN (http://www.stan2web.net/), any kind of data quality evaluation procedure could be used in the first step, but the uncertainty of input data must be expressed using normal probability density functions (defined by mean and standard deviation). Data reconciliation is then performed using a Gauss-Jordan elimination process and the uncertainty of the results is derived using Gaussian error propagation (second step). The resulting material flows can be displayed together with the flow uncertainty in the Sankey style diagram and rounded to significant digits in compliance with the calculated uncertainty.

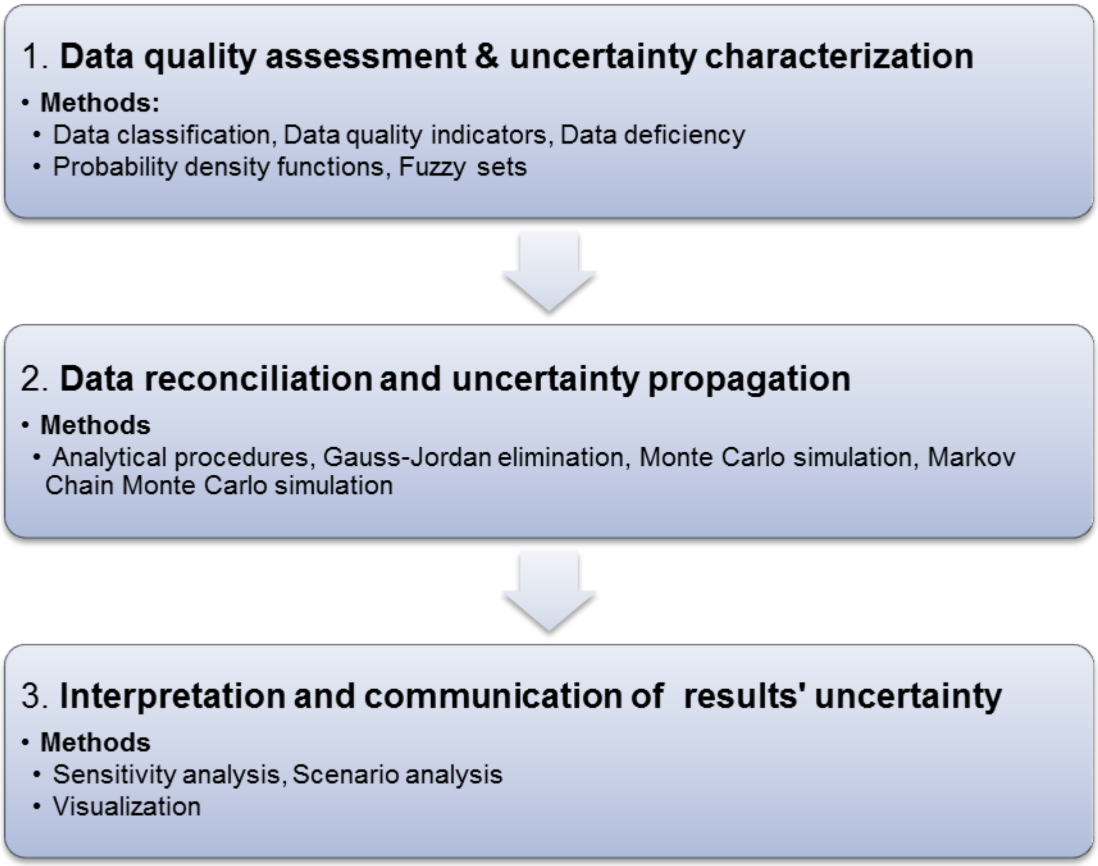


**Figure 1** **Major steps of uncertainty treatment in material flow analysis (MFA)**

## Case studies: uncertainty of recycling rates

The effect of uncertainty in MFA on the material efficiency of anthropogenic resource systems is illustrated for two case studies. In the first case, Aluminium management in Austria is addressed with a focus on the determination of the old scrap recycling rate. In the second case, the recycling of Palladium from end-of-life consumer products is the focus. The generic material flow structure underlying the case studies is shown in Figure 2 together with the respective scope of the investigations. For both studies, the effects of inherent uncertainties on the recycling levels are illustrated and consequences with respect to MFA as a basis for resource management are discussed.

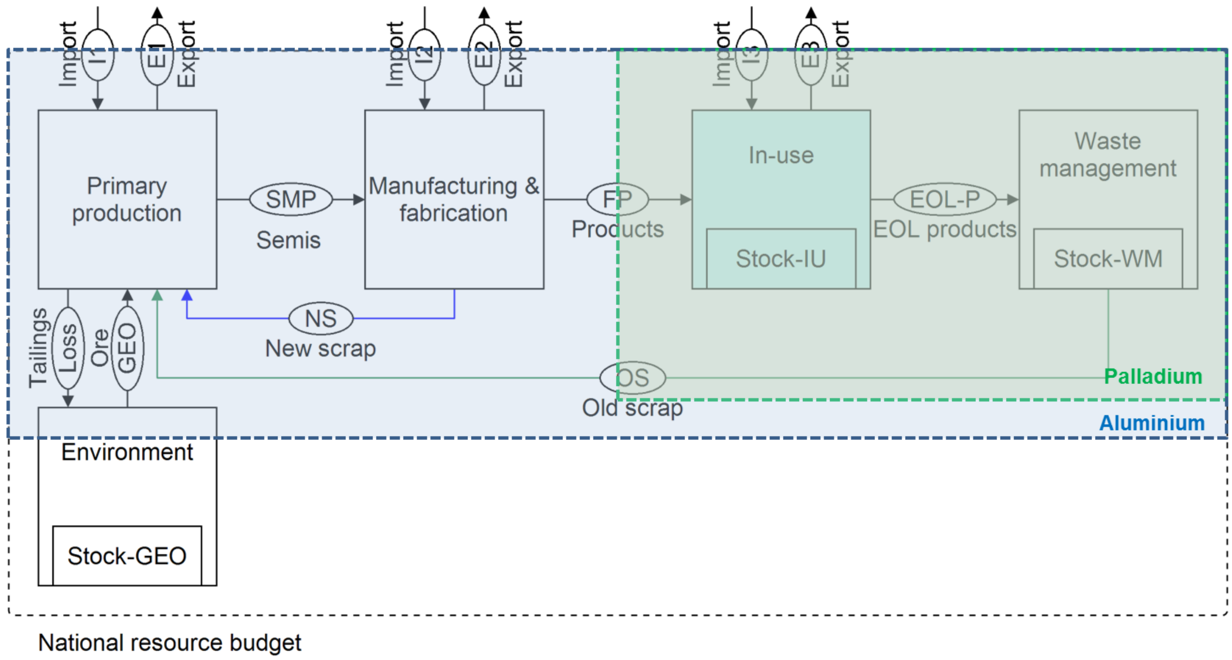


**Figure 2** **Generic national material flow model indicating the scope of the case studies: Al use in Austria (blue shaded area) was investigated along the whole lifecycle (there is no (longer) bauxite mining in Austria). Pd flows in Austria were determined with a focus on flows in consumer products and wastes (green shaded area).**

### *Al scrap recycling in Austria*

Aluminium (Al) is the most widely used non-ferrous metal and secondary Al production is a major industry sector in Austria, which produced a little less than 400,000 metric tons of Al per year in 2010 (Buchner et al. 2014). Around 80% of the Al raw material input was constituted by scrap, highlighting the secondary raw material dependency of the Austrian aluminium industry. In Austria in 2010, 64% ± 29% (relative standard deviation) of end-of-life Al was collected for treatment in Waste management (relates to the flow EOL-P in Figure 2) and 83% ± 27% of the collected Al was directed to recycling as old scrap (OS flow in Figure 2). Overall, domestic scrap generation (NS + OS in Figure 2) made up at least 20% to a maximum of 50% of the scrap input to production (cf. Buchner et al. 2014). The substantial uncertainty related to the actual extent of domestic scrap utilization originated mainly from the high volume of foreign scrap trade. In particular, the indeterminacy of old and new scrap flows in trade statistics impaired a reliable evaluation of domestic old scrap recycling (see

Figure 3). Based on the available information, the old scrap ratio (OSR, share of old scrap in the total scrap input) in Austrian secondary Al production could range from virtually zero to as high as 66%. The minimum is related to a high share of new scrap in imports (75% in Figure 3) and low shares of new scrap in exports (e.g. 25 or 50% in Figure 3). If the share of old scrap in imports is high (e.g. 75% in Figure 3), the old scrap ratio of secondary production reaches the upper end of the specified range. As a consequence, the material flow results do not allow for a reliable evaluation of resource efficiency of Al management in Austria despite the relatively high confidence in the mass flow results (i.e. the relative standard deviation of scrap flow values lies between 3% and 27%, cf. Buchner et al. 2014). This is because, unlike old scrap, the recycling of new scrap does not directly contribute to raw material and energy or emissions saving (Chen 2013). Ultimately, more new scrap generation may mean lower material efficiency in Al processing, potentially causing higher energy use and greenhouse gas emissions. Hence, in order to evaluate the resource efficiency of Al use in Austria, a higher resolution of trade data concerning old (=post-consumer) and new (=manufacturing and fabrication) scrap would be required. The lack of such information introduces substantial uncertainty concerning the type of scrap used in secondary production, impairing conclusions about the actual Al scrap qualities required to sustain the (Austrian) Al cycle.

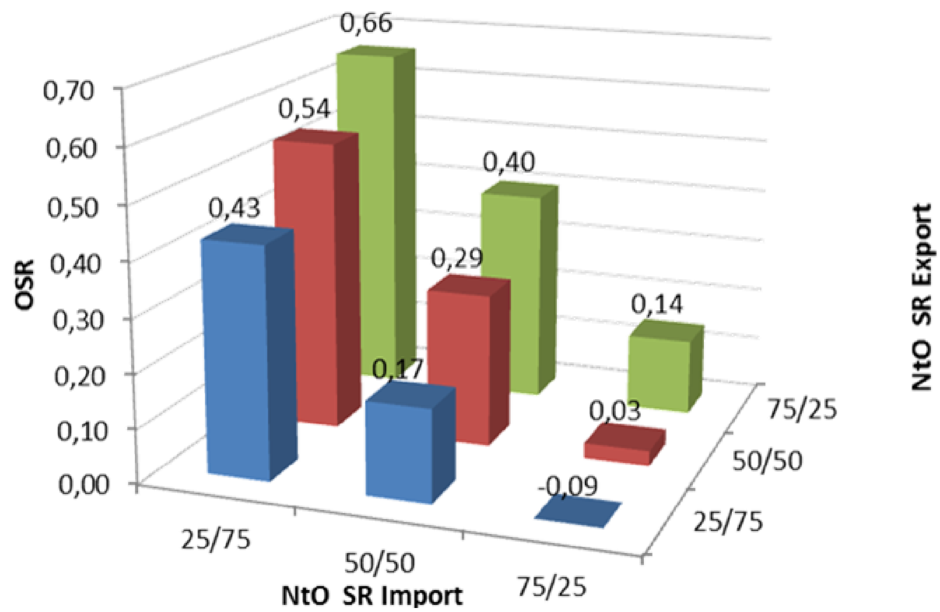


**Figure 3** **Relationship between old scrap ratio (OSR) in domestic secondary production and new to old scrap ratios (NtO SR) of imports and exports (based on Buchner et al. 2014).**

*Palladium recycling from consumer products in Austria*

Palladium (Pd) was designated a critical raw material by the EU (EC 2014). The major flows of Pd in Austrian consumer products are constituted by car catalytic converters and electronic equipment (cf. Laner et al. 2015). In 2011, only about 150 kg out of 1220 kg of Pd consumed in final products (based on mean values) were directed to Waste Management (EOL-P flow in Figure 2); the rest is either accumulated in the in-use stock, exported after use or its fate is unknown. Due to the relatively poor data situation in general and in particular concerning the content of Pd in the various products, fuzzy sets were used to define the possible and most likely range for all input values of the material flow model (cf. Figure 4). Hence, for each material flow the modelling resulted in a possible range of values, including a range of most likely values. The mathematical handling thereby enabled a direct translation of the vagueness in the input data into the uncertainty of the model results. Based on these results, between 20 and 100% of Pd in EOL products were directed to waste treatment, with a most likely value for the collection ratio from 35 to 40%. Out of this collected Pd, between 15 and 91% were recovered as Pd old scrap (Pd input to Waste management directed to the OS flow in Figure 2), with a most likely scrap recovery rate ranging from 58 to 78%. The corresponding old scrap flow had a possible range of 16 to 250 kg Pd per year, with the most likely value being between 93 and 127 kg Pd per year (see Figure 4). Because there was no relevant secondary Pd production in Austria in 2011, Pd old scrap was exported for recycling abroad.

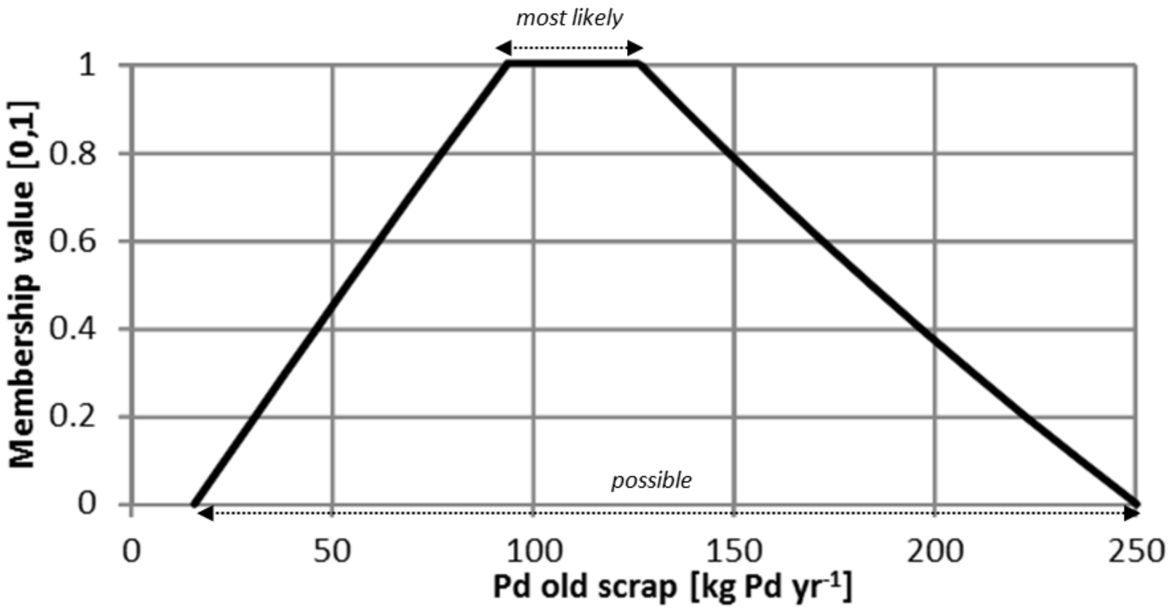


**Figure 4 Resulting possible and most likely ranges for the Pd old scrap flow (based on Laner et al. 2015)**

Based on the results, the overall efficiency of Pd recovery from end-of-life consumer products in Austria in 2011 (collection ratio · recovery ratio) possibly ranged from 3 to 91% and was most likely between 20 and 31%. Consequently, the limitations related to input data had a direct effect on the reliability of material efficiency measures for Pd management in Austria. In particular, the content of Pd in different consumer products, which varied strongly over time and product types, caused substantial uncertainty with respect to actual Pd recovery rates. Hence, in such situations of limited knowledge about the resource flow levels, the designation of recovery or recycling rates as nominal values is not sufficient and may be misleading. Robust resource management decisions can only be made in consideration of data constraints and uncertainty. The rigorous handling of the latter provides an incentive to improve the material flow database as well as the basis for credible decision support while still acknowledging limited system understanding.

### *Synthesis of case study findings*

The case study evaluations showed that limitations of material flow data and their handling in the material flow model significantly affected the reliability of material efficiency measures such as collection, recovery and recycling rates. The transparent and consistent characterization, handling and communication of uncertainty in MFA is of crucial importance for improving the quality and availability of material flow data as well as for giving robust recommendations related to more efficient resource management.

In the case of Al management in Austria, the available data allowed most Al flows in the system to be estimated with relatively high confidence (i.e. low uncertainty). However, the lack of knowledge about the types of scraps imported and exported caused substantial uncertainty with respect to the resource efficiency of domestic Al recycling since the share of old scrap utilization in secondary production is highly indeterminable. As a consequence, little knowledge about the potential of domestic Al scrap to satisfy the scrap demand of the Austrian Al industry can be gained from the analysis of Al mass flows.

In the case of Pd flows in consumer products in Austria, the availability and quality of material flow data was relatively poor. In particular, the lack of knowledge concerning the content of Pd in products over time and with respect to diverse product types caused significant uncertainty with respect to material flows. Therefore, a concept based on fuzzy sets was used to express and propagate uncertainty in the material flow model. The designation of possible and likely ranges highlighted that material efficiency indicators related to the collection and recovery of Pd from end-of-life consumer products are laden with substantial uncertainty. The weaknesses of the material flow database directly affected the confidence in the material flow results, which allowed critical input data to be identified with respect to the recovery of Pd from EOL consumer products. Based on this knowledge, effective measures can be taken to increase the reliability of MFA-based decision support for resource management.

**Conclusions**

In order to increase the material efficiency of resource systems, reliable material flow-based measures are crucial to evaluate current use patterns and monitor progress towards improved resource efficiency.

► Transparent and consistent uncertainty treatment in MFA includes i) data assessment and uncertainty characterization, ii) data reconciliation and uncertainty propagation, iii) consequent interpretation and uncertainty communication.

► The case study results highlight that limitations of material flow data have a direct effect on evaluating the material efficiency of national resource budgets, which can cause significant uncertainty concerning the actual performance of material management.

**Recommendations**

Transparent and consistent characterization, handling and communication of uncertainty should become standard practice in MFA. Therefore, the methodological state-of-the art should be translated into easy-to-use tools. Furthermore, a link between the quality of material flow data and the confidence in the material flow results should be established and suitable methods for visualization should be further explored.

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