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Material flow analysis as basis for efficient resource management – the case of aluminium flows in Austria

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Abstract – Aluminium (Al) consumption growth exceeded those of all other major metals over the last decades. The main driver for this development is the broad range of applications for Al and Al-alloys. As the growth in consumption went along with an increase of anthropogenic stocks and flows of Al, information about material cycles became a crucial issue in terms of resource management. In this study a comprehensive material flow analysis (MFA) of the flows and stocks of Al in Austria for the year 2010 is conducted. The focus of the presented Al balance is on data harmonization and plausibility checks, both based on extensive data and literature research. The stock of Al is derived from bottom-up calculations indicating a total stock of about 260 kg Al per capita with an annual growth of 11 ± 3.1 kg/cap yr in 2010. Total old Al scrap generation is calculated to be 7 ± 1 kg/cap yr. For considering data quality aspects of single input data an adopted method for uncertainty assessment has been applied to the different material flows. This allowed a consistent evaluation of uncertainties within the material flow model. Due to the substantial uncertainties associated with end-of-life Al flows and their significance for secondary Al production in Austria, a better data base is needed in order to evaluate and optimize national Al scrap utilization in secondary production. Therefore, a dynamic MFA model will be built for Austrian Al flows and, in conjunction with the results from the static analyses, will provide a reliable decision basis for future Al resource management.

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Since Al exhibits unique material properties in various aspects (lightweight, flexibility, corrosion resistance, conductibility) it is the most widely applied metal after iron [1]. Besides increasing usage in building applications, Al is a promising material for breaking the weight spiral [2] considering innovative (lightweight) transportation concepts. In spite of substantial savings in the use phase, high emission (fluorides, perfluorocarbons, polyaromatic hydrocarbons, sulphur dioxide and carbon dioxide) and severe environmental impacts (red mud) of primary Al production must be taken into consideration [3]. In 2007 global Al ingot production amounted to 75.5 million tonnes with a scrap ratio of approx. 25% [4] and a total demand for Al products of 45 million tonnes [5]. Production of secondary aluminium requires only 10% of the energy needed for primary production [6].

Particularly regarding energy consumption and reducing emissions, facilitating Al recycling will be an adequate approach, however, with the percentage of secondary Al limited by the ratio of available scrap and total aluminium demand [7]. Nevertheless companies in regions with restricted access to primary resources and high environmental obligations (i.e. European Union) will further extend usage of Al scrap. In this context the use of material flow analysis (MFA) forms the basis for improving existing systems [4]. MFA studies providing detailed information on Al flows and stocks in various stages of the life cycle have been carried out by different authors. Some of them are briefly reviewed below.

A model on global Al flows in 2007 is published by [5, 8] evaluated material efficiencies for five different Al products according to existing production and processing

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routes. Dynamic MFA studies on national and global Al flows have been published by [9–12] using statistical data on production and processing as well as data on foreign trade of Al and Al goods. In addition to quantitative Al balances, dynamic MFA studies have also focused on material qualities [13, 14]. References [15, 16] focused on future trends of Al scrap from ELVs (end-of-life vehicle). A dynamic MFA was applied on the global vehicle cycle and a potential surplus in low quality scrap from ELVs is predicted within the next decade. An optimization model for Al scrap flows was also presented by [17].

In this study, we present an MFA of Al flows in Austria for the year 2010. Extensive data research has been carried out and information originating from official statistics, individual statistics from industrial unions, institutional reports, individual companies, and expert estimates are used to establish the Austrian Al balance. The main objective of the presented analysis is to deliver a detailed image of the national anthropogenic Al cycle. In this endeavor, cross-checking between different data sources and plausibility checks using the material flow model is of crucial importance to arrive at realistic estimates for the stocks and flows of Al at a national level. Additionally an adopted method of uncertainty assessment is applied on the data sources used. Existing in-use stocks are estimated using a bottom-up approach (i.e. based on the Al contents in various applications and the number of products in a specific stock the total Al stock is calculated) in order to relate flows and stock additions to present Al stocks. Providing fundamental knowledge about the system and the available data sources for describing the Austrian Al budget is a main aspect of this MFA. In order to conduct further research on system optimization in terms of material efficiency and quality aspects, profound knowledge of the system is a prerequisite.

1 Material and methods

1.1 Material flow analysis (MFA)

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time [18]. Due to the methodology of MFA the system is defined by spatial and temporal boundaries. The spatial boundary of the study is the geographical border of Austria and the balance is established for the year 2010. All numbers given are on the basis of Al content and in 1000 tonnes, only metallic Al flows are considered and the software STAN [19] is used to conduct the MFA.

1.2 Austrian aluminium balance

In Figure 1 an aggregated model of the aluminum flows in Austria is shown. The lifecycle of Al is illustrated using five main stages, namely production/trade, manufacturing/trade, trade of Al containing products, in-use and waste management with sub processes and sub flows in every system. The main direction of Al flows is from production (left) to waste management (right). Since primary Al production in Austria stopped in 1993, production refers to the output of refiners and remelters of secondary Al industry.

The "sec. production/trade" process combines relevant flows of secondary Al production. Statistical data for the total amount of secondary Al is publicly available from national statistics [20]). Net imports of Al scrap are considered as well as imports and exports of unwrought Al using statistical data. Losses are considered due to exports of salt slags [21, 22]. Desoxidation Al for steel industry and Al powders are considered within the flow "diffusive and destructive use", since Al in this application is lost for the Al cycle in terms of recovery. This assumption is justified as in Austria Al powder is mostly directed to pigments and other chemical uses that are not available for future recovery. For processing routes of semis (rollings, extrusions, castings) a balancing of imported unwrought material with processing capacities has been carried out as well as a calculation concerning the processing scrap generated.

In the process "manufacturing/trade" foreign trade of Al semis and Al goods is considered. New scrap originating from manufacturing of semis is calculated according to material efficiencies from references [10, 23]. The split up of semis consumption to end

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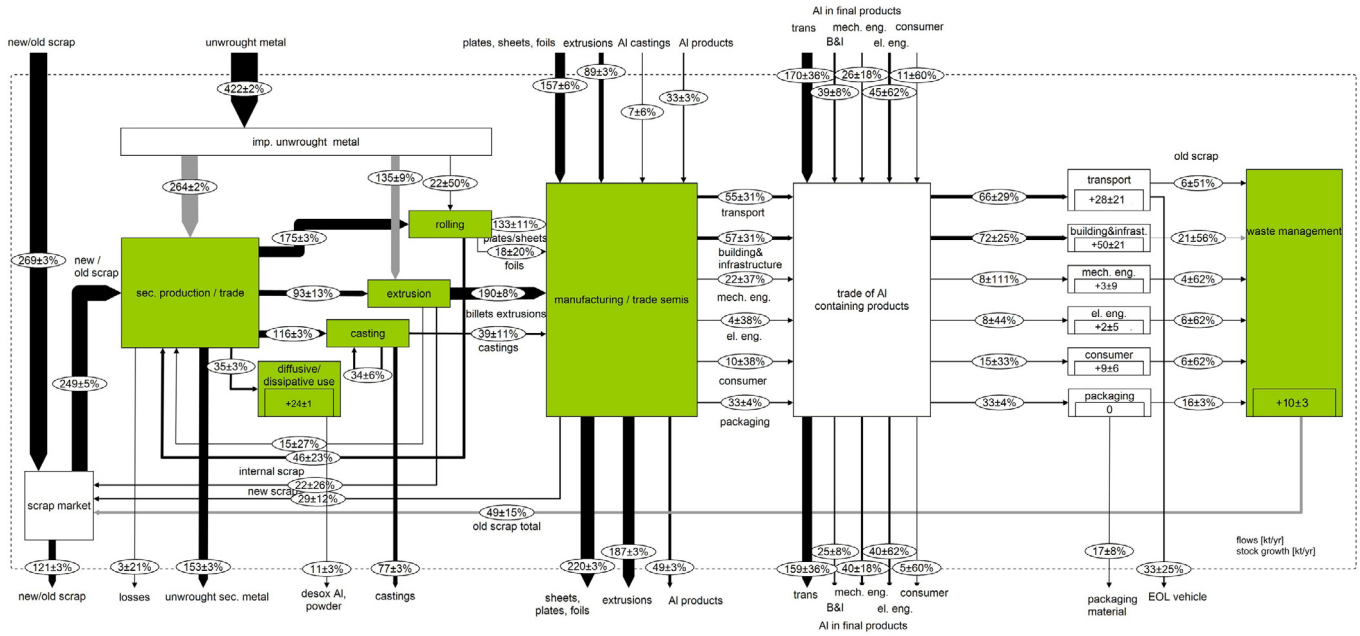


Fig. 1. Static MFA model of Austrian Al flows 2010 (based on [24]).

use applications is conducted due to national and European data [25, 26].

Relevant import and export flows of Al containing products are obtained from foreign trade statistics [27] based on SITC rev.4 classification and considered within the process "trade of Al containing products". Over 600 SITC positions concerning all different in-use sectors, namely transportation, building and infrastructure, mechanical engineering, electrical engineering and consumer have been taken into consideration, but were finally aggregated to 57 main categories. The average Al content for every SITC code is taken from references [1, 10, 28–30]. Concentration and uncertainty levels for specific SITC codes were assumed to be equal for imports and exports.

The "In-use" stage finally shows national Al consumption by end uses. For determining stock increase of Al the total old scrap amount is derived from scrap treated in various "waste management" processes, using previous studies [31–33] and individual data from national recyclers [34, 35].

The process "waste management" is representative for all recycling routes of Al, considering scrap metal trade and separate collection, as well as shredding and sorting of residues from municipal solid waste (MSW) treatment. European data on old scrap generation [36] in combination with information from national data [22, 34, 35] is used for allocating the total amount of old scrap to the given in-use sectors. Furthermore exports of end of life (EOL) vehicles and exports of packaging material are considered separately thereby tracking the change in inventory of the former. Data on exports of packaging material is available from [35].

In this work an adapted concept of uncertainty quantification, based on the methods of [37, 38], is used for a systematic assessment of input data uncertainty. Therefore selected criteria (reliability, completeness, temporal correlation, geographical correlation) of the existing pedigree matrix concept are considered for the determination of a basic uncertainty score. For every datum (flow quantities, Al concentrations and transfer coefficients) and every criterion a score between 1 (good quality) and 4 (bad quality) is defined. In a next step uncertainty ranges are determined for every datum through a combination of the basic uncertainty scores with sensitivity scores from an additional matrix of sensitivity levels. Different uncertainty ranges are thereby assigned to every datum differentiating between three sensitivity levels (low, middle, high). The described second step of sensitivity consideration is

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used in order derive a more refined assessment of uncertainties for the material flow system e.g. temporal imperfection of production data are more critical than temporal imperfections on material efficiencies in production. Basic descriptions and formulas of this system of uncertainty calculation are available from the work by [39], which is currently under development.

The existing in-use stocks for the various sectors are evaluated by bottom-up approach using national inventory statistics and information about the average Al content in various appliances. As the uncertainties in the evaluation of Al in-use stocks are high, the procedure should be regarded as a screening approach and stock estimates will be refined using further analyses in the future.

2 Results and discussion

2.1 Austrian aluminium flows

Figure 1 shows the Austrian aluminium flows of 2010. Total production of secondary aluminium amounts to about 400.000 t yr^{-1} in 2010 with a total input of aluminium scrap of 310.000 t yr^{-1} ± 36%. Net imports of unwrought metal amount to 269.000 t yr^{-1} ± 3%, which is partly allocated to the ingot casting process and partly directly allocated as a feed material for casting and extrusion. Internal scrap is calculated for integrated production sites to 61.000 t yr^{-1} ± 36% and for processing plants to 22.000 t yr^{-1} ± 26%. By balancing the foreign trade of extrusions with national billet production and national extrusion capacities a share of 135.000 t yr^{-1} ± 9% billets from total unwrought metal imports is determined. New scrap from the extrusion process is recycled in-house for integrated production plants (15.000 t yr^{-1} ± 27%) and partly traded as new scrap on the market in case of production plants without smelting facility (22.000 t yr^{-1} ± 26%). About 35.000 t yr^{-1} of Al originating from national production and imports of unwrought metal is used for destructive and diffusive uses. The amount of 24.000 t yr^{-1} ± 5% of Al additions in stock equates to the national production of desoxidation Al and powder deducing net-exports. About 150.000 t yr^{-1} ± 13% of rolled products are leaving national production, foils are attributed to foils for national consumption. The flow of billets and extrusions includes extrusions from national production (114.000 t yr^{-1} ± 3%) as well as trade flows of billets and extrusion with cannot be clearly distinguished from statistics. Total production of castings amounts to 116.000 t yr^{-1} ± 3%, with 66% being exported and 34% for national consumption.

Total input into the "In-use" originating manufactured semis from national production and net-imports of semis is dominated by transport (55.000 t yr^{-1} ± 31%) and building&infrastructure sector (57.000 t yr^{-1} ± 31%). A breakdown of national Al flows into different semi-products is obtained by applying data on the average European consumption by "end-use" to the calculated flows (Fig. 1). Only for extrusion a Austrian specific breakdown by end use sectors (including imports) is available [25]. For rollings and castings national production together with net-imports are allocated to different end uses based on statistics referring to the average consumption pattern of Al in Europe [26].

The vast majority (78%) of national produced castings is used in transport applications, 7% are used in building&infrastructure and 14% in mechanical engineering. More than 55% of extrusions are used in building&infrastructure, about 17% are used in transport and 12% in mechanical and electrical engineering. For the national consumption of rolled products almost half (50%) is used in packaging applications, followed by building&infrastructure (23%) and the transport sector (10%). Electrical engineering and production of consumer goods represent the two in-use sectors with the lowest consumption of Al.

Concerning Al flows from foreign trade of final goods, for all categories, except mechanical engineering, a net import of Al into national use is observed. Highest Al flows are observed from trade of goods in transportation applications, although net-imports (11.000 t yr^{-1} ± 36%) are comparatively small. Highest Al net-imports are due to goods for building and infrastructure applications (14.000 t yr^{-1} ± 8%), mechanical

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engineering applications is the only sector with a net-export (14.000 t yr^{-1} ± 18%).

The total amount of Al entering the "In-use" phase consists of Al from national production and manufacturing and Al net imports of final products. The net Al import flow from the trade of Al containing products is about 7% of total domestic in-use input. Highest inputs exhibit transport (66.000 t yr^{-1} ± 29%) and building&infrastructure (72.000 t yr^{-1} ± 25%) sector. In order to derive numbers for net stock increase, generation of old scrap, EOL vehicle exports (33.000 t yr^{-1} ± 25%) and exports of Al used as packaging material (17.000 t yr^{-1} ± 8%) are considered separately. Finally 60.000 t yr^{-1} ± 13% of Al old scrap entered "waste management" in 2010, which leads to a net stock increase of the "In-use" stock of 92.000 t yr^{-1} ± 63.000 yr^{-1} or 11 ± 7.5 kg/cap. For reasons of limited data availability on quantities of old scrap generation from "In-use" sectors uncertainties of old scrap flows are comparably high. Together with high uncertainties from imports and exports of goods the in-use stocks increase is also subjected to high uncertainty. About 2/3 of EOL vehicle exports are due to exports of passenger cars, the remaining share is due to export of commercial vehicles and bikes.

2.2 Uncertainty assessment

Data on Al flows in this study is derived from a plurality of data sources. When conducting a MFA based on explorative data analysis, the evaluation and assessment of uncertainties becomes an essential aspect for usage and interpretation of the results [40].

Fairly good data is available for national Al flows at the production and processing level with uncertainties between 3–20%. Since precise company data is not available for all production sites in Austria, scrap flows from production and processing (in-house and new scrap) exhibit higher uncertainties (23%–27%). Foreign trade of semis only adds little uncertainty to the system (3%), since statistical data is well reported. Higher uncertainties (31%–38%) have to be considered in allocating Al flows from national manufacturing to end use sectors, since national data is only partly available and European average values have to be used as well. In foreign trade of Al containing products uncertainties are mainly imposed by hardly available information on Al concentrations of various goods. Although uncertainty on total old scrap flow is comparatively low (15%), old scrap flows from specific end use sectors exhibit high uncertainties (around 60%) due to missing data on allocation of the total flow to certain end use sectors. Even though the quantity of uncertainty ranges is subjected to the modeler's practice, it can be concluded that uncertainty increases with increasing level of detail. Especially bottom-up data at the in-use stage (consumption and old scrap generation) are hardly available, expressed by high uncertainties at this stage of the life cycle. Nevertheless main Al flows in the national system can be determined quite properly and a closed balanced within acceptable uncertainty intervals is derived.

3 Analysis of aluminium stocks

The Al in-use stock is calculated without the additions of the balance year 2010 and amounts to 2.200.000 t or 260 kg/cap. Major quantities (about 48%) of the analyzed Al stock, are stored in buildings and infrastructure facilities, followed by 34% in transportation applications, 16% in electrical infrastructure and only about 2% in consumer goods (Fig. 2b). For the two biggest sectors (transport and building&infrastructure) a detailed composition of the existing stocks is shown in Figures 2c and 2d. A major Al amount (63%) of buildings is stored in industry, commercial and public buildings. Residential buildings "host" about one third of the present Al in-use stock. Analyzing the stock of the transportation sector a significant share of Al in cars becomes obvious (74%). Different penetration of Al in cars over time is considered according to [29, 41, 42]. Share of Al stored in commercial vehicles is about 20% of the total transportation stock.

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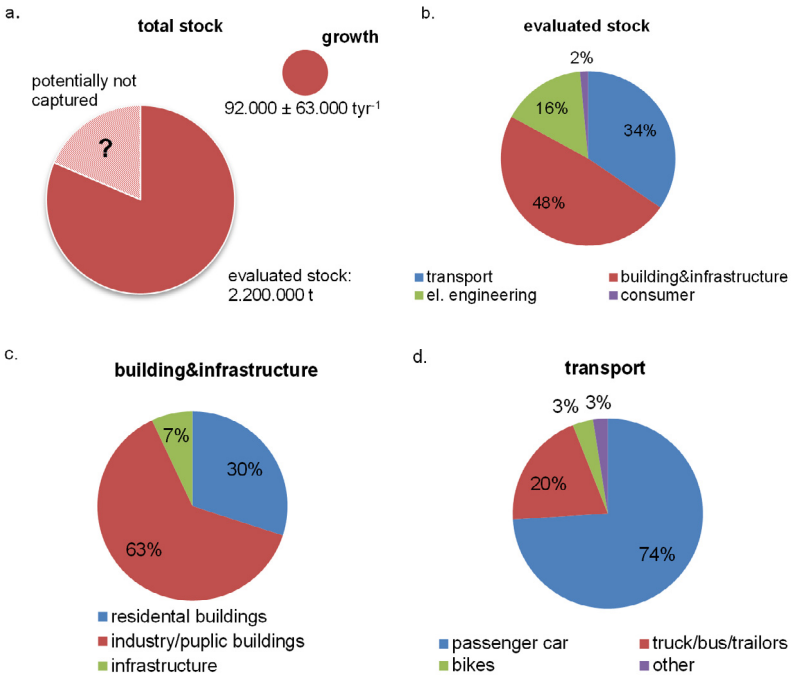


Fig. 2. Breakdown of the existing in-use stock. Figure 2a shows the total stock and the stock increase in 2010. In Figure 2b a breakdown of the total stock in different in-use is shown. Figure 2c illustrates a breakdown of building and infastructure sector and Figure 2d a breakdown of the transport sector (based on [24]).

4 Conclusion

Austrian Al flows were analyzed in detail in this study. Growth of in-use stock was determined by calculating inputs into and outputs from in-use phase. In order to determine the total amount of old scrap, a comprehensive analysis of the waste management system was conducted. The uncertainty analysis showed that the uncertainties about flows tend to increase in the latter stages of the Al life cycle due to missing data. Based on static modelling a detailed understanding of the Austrian Al system could be gained in this study. Bottom-up analysis of the in-use stock should be regarded as screening level results. A comparison with other studies indicates that not all Al in-use can be captured by analyzing inventory data (bottom-up). The Al amount of 260 kg/cap calculated in this study is below the amount of (320–500 kg/cap) for European Countries derived from dynamic models [9,10,43] Short comings of the analysis are apparent with respect to Al flows associated with long-lived products; hence dynamic modelling should be used to derive better estimates (e.g. scrap generation, in-use stock growth). Consequently, future work will focus on the assessment of long term effects using a dynamic modelling approach. Cross-checking and validation between the existing static and the upcoming dynamic model should provide additional information about the reliability of material flow analysis results.

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