Doctoral Thesis

Dynamic material flow modelling as a strategic resource management tool for Austrian aluminium flows

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Dissertation

Dynamische Stoffflussmodellierung für die strategische Bewirtschaftung österreichischer Aluminiumflüsse

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Abstract

Constantly increasing demand for raw materials has been going along with a build-up of anthropogenic material stocks. In combination with limited access and utilisation of primary resources in some world regions (e.g. European Union), the availability of secondary raw materials has become a common interest. Regarding two of the quantitatively most important non-ferrous metals (aluminium (Al) and copper), the global secondary production already contributes 15% and 30% to the total global production. Knowledge about historical, current and future material stocks and flows in society are therefore of crucial importance for a knowledge based future resource management.

In this thesis a static and a dynamic material flows model of Austrian Al flows is developed. The static material flow model (Paper 1) gives a detailed insight in the national system of Al flows in 2010, including a detailed view on the waste management process as well as on the scrap market. From this model a total in-use stock increase of 92 kt (11 kg/cap.) and a total old scrap generation of 59 kt (7 kg/cap.) is calculated. The total scrap share in national secondary production is around 80%, with a calculatory old scrap share between 0% and 66%. The dynamic material flow model (Paper 2) evaluates historical Al flows in order to estimate current in-use stocks as wells as trends in old scrap generation. From this model a current total in-use stock of around 3.1 Mt (360 kg/cap.) is estimated for 2012, which corresponds to an increase of by a factor of 3.8 over the past thirty years. Approximately two-thirds of total in-use stocks are present in the Building and Infrastructure as well as in the Transport sector. Total old scrap generation increased by a factor of 3.4 in the same period and is currently around 130 kt (14 kg/cap.) including collection and recycling losses as well as vehicle exports.

In order to estimate future development of in-use stocks and old scrap generation the data from the historical (data based) dynamic material flow model (timely resolved in-use stocks) are combined with forecasts on future Al consumption (Paper 3). For the Transport, the Buildings and Infrastructure and the Electrical Engineering sector a stock-driven approach is used and for the Mechanical Engineering, Consumer and Packaging sector an input-driven approach is used for modelling future Al flows. Total in-use stock and total old scrap generation are expected to increase to 530 kg/cap. and 31 kg/cap. respectively by 2050. By comparing future old scrap generation with future industrial Al demand as well as with final Al demand, the future self-supply potential (independence from Al imports) is calculated. From an industry perspective self-supply from secondary Al sources is not expected to rise above 12% and from a final demand perspective self-supply is not expected to rise above 40%. Enhanced recycling of Al old

scrap could increase self-supply by another 8% and 27% respectively.

Finally future self-supply is evaluated under the current recycling practice with respect to wrought and cast alloys. Results indicate that the current supply from mixed old Al scrap is already exceeding national final demand of cast alloys and sorting technologies are required in order prevent a surplus of mixed old Al scrap over final cast Al demand in future. Sorting technologies become even more relevant when Al is going to be used more intensively for structural components in cars in the future (light-weight constructions). Even though generation of mixed Al scrap exceeds national final cast Al demand, it will mostly like remain beneath national foundry casting demand. Environmental and resource management aspects of the current recycling practice are briefly discussed at the end of this thesis.

Kurzfassung

Ein fortwährender Anstieg des Rohstoffbedarfs über die vergangenen Jahrzehnte resultiert in einem beträchtlichen Aufbau anthropogener Lager. In Kombination mit einem begrenzten Vorkommen und einer eingeschränkten Nutzung von Primärressourcen in bestimmten Weltregionen (z.B. Europa), führt dies zu einem stetig steigenden Interesse an sekundären Rohstoffen. Bei den mengenmäßig und wirtschaftlich wichtigen Nichteisenmetallen Aluminium (Al) und Kupfer liegt der Anteil der Sekundärproduktion an der globalen Gesamtproduktion bereits bei 15% bzw. 30%. Der zunehmende Einsatz von Sekundärrohstoffen macht daher Informationen und eine Datenbasis bezüglich historischer, aktueller und zukünftiger Materialflüsse und Lager unabdingbar für ein wissensbasiertes, zukunftsorientiertes Ressourcenmanagement.

Als primäres Ziel dieser Arbeit wurde ein statisches und ein dynamisches Stoffflussmodel der Österreichischen Al-Flüsse entwickelt. Das statische Stoffflussmodell (Paper 1) gibt einen detaillierten Einblick in das nationale Al-Stoffflusssystem für 2010. Dabei wird im Speziellen die Abfallwirtschaft sowie der nationale Schrottmarkt im Detail betrachtet. Dem statischen Modell folgend, ergibt sich für das Bilanzjahr 2010 ein Anstieg des nationalen Nutzlagers von 92 kt (11 kg/Pers.) sowie ein Altschrottanfall von 59 kt (7 kg/Pers.). Der Schrottanteil in der nationalen Sekundärproduktion beträgt ca. 80%, mit einem kalkulatorischen Altschrottanteil zwischen 0% und 66%.

Im dynamischen Stoffflussmodel (Paper 2) werden datenbasiert die historischen Al-Flüsse untersucht, um daraus auf die derzeit im Nutzlager befindliche Al-Menge sowie auf die Entwicklung der Altschrottflüsse schließen zu können. Aus diesem Modell ergibt sich ein nationales Gesamtlager von ca. 3,1 Mt (360 kg/Pers.) für das Jahr 2012. Dies entspricht einem Anstieg um den Faktor 3,8 in den letzten 30 Jahren. Die beiden wichtigsten Sektoren in Bezug auf das nationale Al-Lager sind der Gebäude- und Infrastruktursektor sowie der Transportsektor. Diese beiden Sektoren zusammen repräsentieren ca. zwei Drittel des anthropogenen Al-Lagers in Österreich. Der Altschrottanfall ist im selben Zeitraum um einen Faktor 3,4 gestiegen und beträgt derzeit ca. 130 kt (14 kg/Pers.) inkl. Sammel- und Recyclingverlusten sowie Fahrzeug-Exporten.

Um die zukünftige Entwicklung der sektorspezifischen Lager und Altschrottflüsse abschätzen zu können, wird das entwickelte Al-Modell (zeitlich diskretisiertes Al-Lager) mit Prognosen über den zukünftigen Al-Verbrauch erweitert (Paper 3). Für die Sektoren Transport, Gebäude und Infrastruktur sowie Elektrische Anlagen wird dafür ein lagerbasierter Ansatz verwendet. Die Sektoren Maschinenbau, Konsumgüter und Verpackungen werden mittels eines verbrauchsbasierten Ansatzes modelliert. Aus diesen

Berechnungen ist abzuleiten, dass das Gesamtlager bis 2050 auf 530 kg/Pers. ansteigen wird. Der Gesamt-Altschrottanfall steigt im selben Zeitraum auf ca. 31 kg/Pers. Aus dem Vergleich des zukünftigen Schrottanfalls mit dem zukünftigen industriellen Al-Bedarf, wie auch mit dem zukünftigen Endverbrauch an Al, lässt sich der theoretische Selbstversorgungsgrad (Unabhängigkeit von Al-Importen) ermitteln. In Bezug auf den industriellen Al-Bedarf ist zu erwarten, dass der Selbstversorgungsgrad bis 2050 nicht über 12% steigen wird. Bezogen auf den Al-Endverbrauch ergibt sich ein rechnerischer Selbstversorgungsgrad von ca. 40% im Jahr 2050. Verstärktes Recycling von Altschrott könnte den Selbstversorgungsgrad in Bezug auf den industriellen Al-Bedarf sowie bezogen auf den Al-Endverbrauch potenziell um weitere 8% bzw. 27% anheben.

Abschließend erfolgt eine Betrachtung des Selbstversorgungsgrades mit einer Differenzierung nach Guß- und Knetlegierungen unter Berücksichtigung der aktuellen Recyclingpraxis. Dabei zeigen die Ergebnisse, dass die derzeit generierte Menge an Al-Mischschrotten den nationalen Endverbrauch an Gußlegierungen bereits übersteigt. Die breitere Anwendung von Sortiertechnologien erscheint daher notwendig und sinnvoll, um dem spezifischen Bedarf an Al-Legierungen besser gerecht zu werden. Vor allem in Anbetracht einer zukünftig potenziell vermehrten Anwendung von Knetlegierungen in Strukturbauteilen von Fahrzeugen erscheint eine verbesserte Schrottsortierung unabdingbar. Obwohl der nationale Anfall an gemischten Al-Schrotten den Endverbrauch an Gußlegierungen übersteigt, liegt dieser dennoch deutlich unter dem industriellen Bedarf an Gußlegierungen. In diesem Zusammenhang werden am Ende dieser Arbeit ökologische Aspekte sowie Fragen des Ressourcenmanagements in Bezug auf ein optimales Al-Recycling diskutiert.

Published articles and author's contribution

Paper 1

In-depth analysis of aluminium flows in Austria as a basis to increase resource efficiency
Hanno Buchner, David Laner, Helmut Rechberger and Johann Fellner
Resources, Conservation and Recycling, 2014 93, 112–123
DOI: 10.1016/j.resconrec.2014.09.016

I personally conducted data research on top-down and bottom-up estimates and generated the static STAN model including the evaluation of the characteristics of the Austrian aluminium flow system.

Paper 2

Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria
Hanno Buchner, David Laner, Helmut Rechberger and Johann Fellner
Environmental Science & Technology 2015 49 (9), 5546-5554
DOI: 10.1021/acs.est.5b00408

I personally conducted data research on top-down and bottom-up estimates. I further developed the dynamic material flow model in MATLAB including the routine for uncertainty analysis and implemented the EASI routine for sensitivity analysis.

Paper 3

Future raw material supply: opportunities and limits of aluminium recycling in Austria
Hanno Buchner, David Laner, Helmut Rechberger and Johann Fellner
The Journal of Sustainable Metallurgy 2015 1 (4), 253-262
DOI: 10.1007/s40831-015-0027-3

I personally extended the dynamic material flow model by forecasts on future aluminium consumption through applying a stock-driven and an input-driven approach. I further evaluated future self-supply scenarios.

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List of Abbreviations

Al Aluminium

cap Capita

CDF Cumulative distribution function

Cu Copper

dMFM Dynamic material flow model

EASI Effective algorithm for computing global sensitivity indices

Eq Equation

ETS Emission Trading System

EU European Union

Fig Figure

kt Thousand tonnes

MCS Monte Carlo Simulation

MFA Material flow analysis

MSW Municipal solid waste

Mt Million tonnes

OSR Old scrap ratio

Sec Section

Si Silicon

t Tonne

Tab Table

yr Year

Zn Zinc

1 Introduction

1.1 Global and regional consumption of metals

Availability of raw materials has ever been the basis for economic growth and well-being in society. Historically raw materials (especially metals) were mostly taken from natural mineral deposits. During the past 60 years primary production of metals increased significantly and led to a considerable transfer of material from the lithosphere to the anthroposphere including a built-up of anthropogenic material stocks (material nowadays present in products like vehicles, buildings, infrastructure facilities etc.). In Figure (Fig.) 1.1 historical global primary production amounts for three of the (quantitatively) most important metals are shown (crude steel left axis, aluminium (Al) and copper (Cu) right axis). Global production of crude steel and Cu has more than doubled during the past 30 years, Al production more than tripled in the same period. Especially lightweight constructions in transport applications (e.g. vehicles) have been a driver of Al demand in recent decades (Hirsch, 2011).

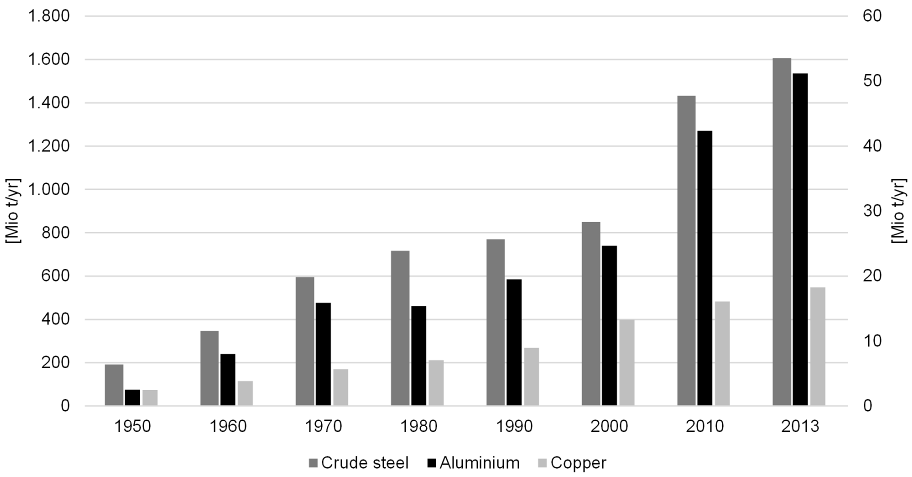


Figure 1.1: Global production of crude steel, Al and Cu (International Aluminium Institute, 2015a; Worldsteel Association, 2015; Matos, 2015)

As the build-up of anthropogenic stocks goes along with a release of material (old scrap) from these stocks, after application specific lifetimes, availability of secondary resources increased considerably during the past decades. Increasing utilisation of secondary resources is indicated by the development of secondary Al production (Fig. 1.2). While secondary production of Al played a minor role before 1970, a significant increase is observed during the past 30 years. Primary Al production increased by a factor of 2, while global secondary production from old scrap increased by a factor of 2.5 (cf. Fig. 1.2) and total secondary production (including new scrap) by a factor of 5 (International Aluminium Institute, 2015b). But data on secondary production is not reported consistently. Data from the International Aluminium Institute states a global secondary production of one third of global Al production in 2006 (12-16 Mt), while the U.S Geological Service reports about 12 Mt. Old scrap shares are estimated between 40% and 50% (OECD, 2015). From the Global Aluminium Recycling Committee (GARC) model (International Aluminium Institute, 2015b) a secondary production of 23 Mt is estimated for 2013, which would result in an secondary production from old scrap of around 11.5 Mt. In parallel secondary production data is reported from the World Bureau of Metal Statistics, where a scrap recovery of 9.1 Mt is reported for 2006 and nearly the same amount for 2013 (World Bureau of Metal Statistics, 2013). Summing up, based on the available data sources current secondary production (from old scrap) is estimated between 9.1 and 11.5 Mt. Independent estimates regarding the share of manufacturing scrap are available on a global and European scale with a percentage of 15% to 17% (Rombach, 2013), not considering processing scrap. However, since all these types of scraps are process-related, they should not be considered as a secondary raw material input since no primary material is substituted in a life-cycle dimension.

Shifting from a global view to a more regional focus of the European Union (EU), it is observed, that the share of primary production in unwrought Al consumption decreased from around 60% in 1980 to 14% in 2013, while the share of secondary production increased from around 26% to 35%. Lacking quantities of total unwrought Al demand (approx. $12\text{x}10^6$ t in 2013) are supplied by imports as indicated in Fig. 1.3a. For countries without primary Al production this trend is even more pronounced. After the close-down of electrolysis facilities in Austria in 1992, secondary production increased significantly and provides nowadays more than two-thirds of national unwrought Al demand (Fig. 1.3b).

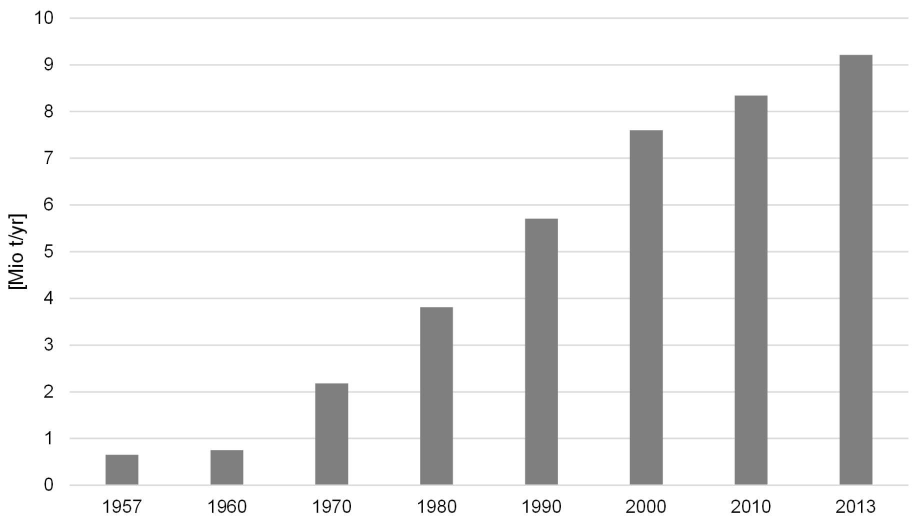
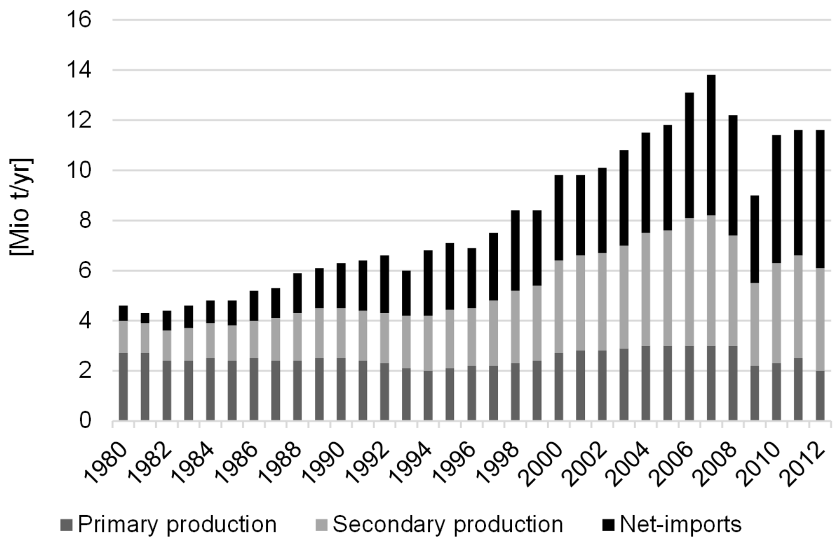


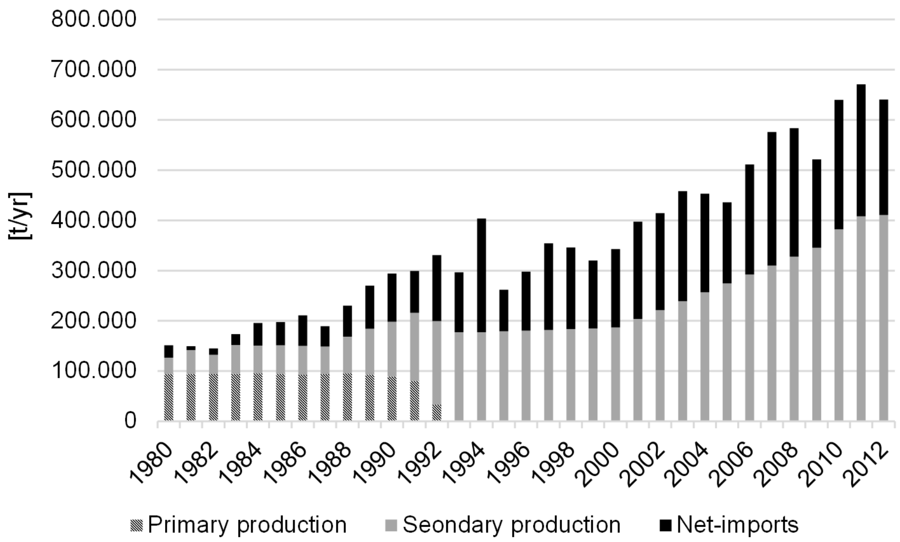
Figure 1.2: Global secondary Al production (World Bureau of Metal Statistics, 1967-2014)

1.2 Primary aluminium production and regulatory costs

The decreasing trend in European primary Al production has been mainly induced by high energy costs, tightened environmental regulations and a scarcity of domestic primary resources. Since 50% total energy requirements in primary production are dedicated to electricity for electrolysis and alumina production (Jirang and Roven, 2010), electricity costs are considered as a crucial factor in primary production. Even though some European smelters operate highly cost-efficient, up to one third of the competitive gap compared to other world regions is due to regulatory costs (e.g. Emissions Trading System (ETS), eco-duties etc.) in the European Union (EU) (Pelkmans et al., 2013). As the European Commission already set new regulations (Commission Regulation (EU) No 176/2014 of 25 February 2014) for reducing the amount of emission allowances during phase 3 (2013-2020) of the ETS in order to stabilize certificate prices, primary production quantities are not expected to increase from today's perspective. Additionally the global market of primary Al has become more competitive because of emerging primary producers in energy rich regions like the Middle East. Primary Al production in the Middle East region increased by 60% from 2008 and is currently close to 4 Mt (Al Attar, 2014), which is already twice the primary production of Europe and 8% of global primary Al production (European Aluminium Association, 2012).



(a) Import dependency EU (European Aluminium Association, 2015c)



(b) Import dependency Austria (Buchner et al., 2015)

Figure 1.3: Historical unwrought Al supply in the EU and Austria by source

1.3 European raw materials policy

Although primary production in European countries has been heavily hit by energy costs and environmental regulations, the European Commission currently intends to raise the share of manufacturing and industry back to 20% of GDP by 2020, in order to foster growth and competitiveness of the European Economy (European Commission, 2014c). Following this target, the availability of raw materials has been identified as one major factor inhibiting growth of industry. In order to tackle the challenges of a secure raw materials supply the Raw Materials Initiative and the European Innovation Partnership (EIP) on Raw Materials have been launched by the EU (European Commission, 2012). Cornerstones of these initiatives are 1) the access to raw materials on the global market under the same conditions than competitors, 2) sustainable extraction of raw materials within the EU and 3) increased recycling and a more effective use of resources. Recycling measures will be guided by the objectives set in the EU's seventh Environment Action Programme for waste management (European Commission, 2011), namely:

- reduce the amount of waste generated;
- maximise recycling and re-use;
- limit incineration to non-recyclable materials;
- limit landfilling to non-recyclable and non-recoverable waste.

Typical solid process residues generated within the primary and secondary Al and Cu production are residues from ore refining (e.g. red mud from alumina refineries) as well as slags and dross from smelting, converting, refining and melting, filter dusts and spent refractory from furnace linings (Schmitz et al., 2006; Apostolovski-Trujic et al., 2007). Turnings, chips and cuttings may further occur in the downstream industry through processing and manufacturing of metal products.

Besides aspects of raw material security, current European environmental and economic policy is additionally focusing on implementing circular economy concepts, where systems should keep the added value in products as long as possible. Environmental benefits and economic growth are additionally expected from keeping resources in the economy when a product reaches end-of-life (European Commission, 2014a). In order to foster development towards a recycling economy, waste management targets (especially regarding an increase of recycling rates) are considered of being amended. Even though recycling of metal scrap is environmental beneficial in most cases, due to high energy demand and emissions in primary production, the real potential of primary raw material substitution from scrap recovery is not very well known. Quantitative estimations of the future scrap availability and the impact of enhanced recycling measures are of crucial importance for setting target-oriented policy actions regarding recycling strategies as well as for waste and raw material management.

The method of material flow analysis (MFA) has been applied in various studies in order to investigate and analyse resource flows and the built-up of anthropogenic stocks. Application of MFA to any material-based system is an effective tool for assessing potentially harmful or beneficial accumulations in stocks and for setting priorities regarding resource and waste management measures (Brunner and Rechberger, 2004). Studies have been undertaken to various extents, from country specific, to regional and further up to global models, mostly addressing metal flows like iron and steel, Al, Cu, chromium, lead and zinc (Chen and Graedel, 2012b). Through analysing inflows into and outflows from a given stock, the stock growth as well as potential future outflows expected from the stock can be calculated. Analysing current flows within a system and projecting future material outflows from anthropogenic stocks provides crucial information for resource and raw material management, which has become a relevant aspect in environmental and economic policy making nowadays.

2 Objectives

As the main goal of this thesis historical, current and future patterns of Al use are analysed, in order to quantify in-use stocks and Al scrap flows. Through quantifying current and future in-use stocks, the secondary resource potential originating from anthropogenic sources can be calculated. Therefore in-use stocks and corresponding inflows and outflows are determined and analysed from various perspectives of secondary raw material use. Based on a initial static MFA study of Austrian Al flows in 2010 (cf. Paper 1), which provides detailed insights into current domestic Al flows, a dynamic material flow model for Austrian Al flows between 1964 and 2012 is developed (cf. Paper 2). Considering achievements of existing dynamic material flow models (dMFMs), a special focus is given to the calibration and validation of the model with independent bottom-up estimates. In order to calculate the development of in-use stocks and future old scrap generation, the dynamic model is complemented with forecasts on final Al demand until 2050 (cf. Paper 3).

Major questions tackled in this thesis:

- How big is the current Al-stock in Austria with respect to common sectors of Al use?
- How can national dMFMs be improved by calibration and validation measures with independent bottom-up estimates compared to global material flow models?
- Which old scrap amount is expected in future and to which extend could primary raw material substituted by old scrap?
- How could enhanced recycling affect self-supply and decrease import dependency?
- Could quality aspects, with respect to cast and wrought alloys, be a limiting factor for Al recycling in a (hypothetically) closed national system?

The following parts of this thesis are headed by a short description of dynamic material flow modelling and a short review on existing studies in that field, with a focus on metals especially Al. Considering existing literature the contribution of this thesis to the field of dynamic material flow modelling and resource management will be shown by summarizing the most important results from the published articles in the Appendix, which have been published in peer-reviewed journals. The first article (Paper 1: *In-depth analysis of aluminium flows in Austria as a basis to increase resource efficiency*) contains a detailed static material flow study of the Austrian flow system in 2010. In the second article (Paper 2: *Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria*) a dynamic material flows system of Austrian Al flows between 1964 and 2012 is established, in order to calculate in-use stocks and old scrap generation using an input-driven top-down approach. The third article (Paper 3: *Future raw material supply: opportunities and limits of aluminium recycling in Austria*) contains an extension of the model in Paper 2, where future in-use stocks and old scrap generation are calculated, using estimates on future Al demand, in order to evaluate future self-supply from scrap sources. In addition to the results from the articles further findings, concerning Al flows associated with process residues in secondary production, Al self-supply and recycling of packaging waste as well as regarding quality aspects of cast and wrought alloy recycling within a confined national system, are shown.

3 State of the art methods and scientific background

3.1 Dynamic material flow modelling

As one of the classical approaches in dynamic material flow modelling historical production and trade data is used to derive final Al demand (inflows into in-use stage) for a given system like a country or even bigger regions. These type of models are called input-driven models. Based on the derived annual inflows into in-use stocks $I(t)$ the outputs of the subsequent periods can be calculated by applying typical, sector-specific lifetime distribution functions $F(t)$ to the $I(t)$ of every period (Fig. 3.2).

Several types of statistical distribution functions come into consideration for describing the residence time of material in the in-use stocks. Normal and Log-normal distribution as well as Weibull distributions (Eq. 3.1, Eq. 3.2 and Fig. 3.1) are often used for describing outflows from previous inflows (Müller et al., 2014). The parameter t is the value at which the function is calculated, α defines the shape of the distribution and β is the scale parameter of the distribution (often used as average lifetime in dMFMs). Regarding the choice of probability distribution functions earlier studies showed, that the choice of distribution parameters, especially the average lifetime of products, exhibits a higher sensitivity on outflows than the choice of distribution type (Melo, 1999).

$$f(t,\alpha,\beta) = \frac{\alpha}{\beta^{\alpha}} t^{\alpha-1} \exp -(\frac{t}{\beta})^{\alpha} \tag{3.1}$$

$$F(t,\alpha,\beta) = 1 - exp - (\frac{t}{\beta})^{\alpha} \tag{3.2}$$

By applying probability distributions on $I(t)$ and summing-up over all outflows from previous I(t) the annual outflow ($O(t)$) of one sector is calculated (indicated in the grey bottom row of Fig. 3.2). In-use stocks are finally derived from the cumulative sum of differences between the inflows and the outflows of each year. A calculation scheme in

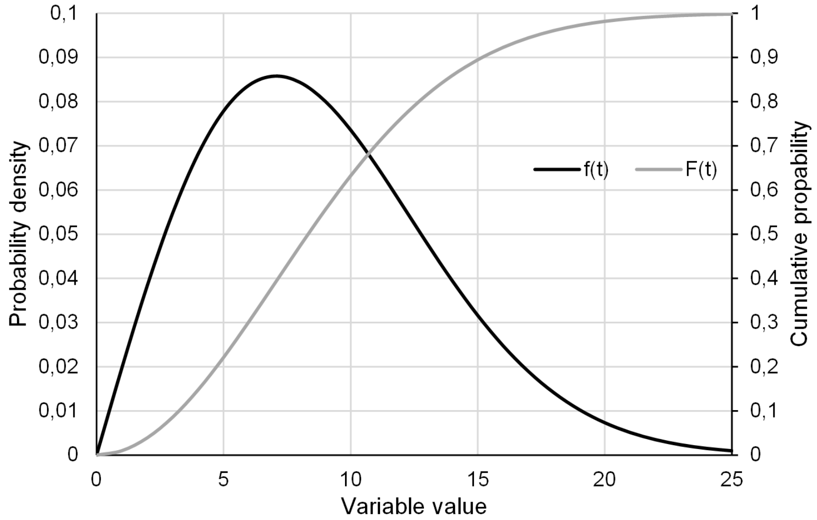


Figure 3.1: Exemplary Weibull density and cumulative density function as applied in the Austrian dMFM

time discrete as well as in integral form is shown in Fig. 3.3. The procedure of balancing inflows with outflows for every time step is usually conducted individually for every sector of Al use, since average lifetimes of products normally differ considerably (e.g. 40 years for Buildings and Infrastructure and a residence time of < 1 year applied on Packaging Material). Transport, Buildings and Infrastructure, Mechanical Engineering, Electrical Engineering, Consumer Goods and Packaging Material are considered being the most important sectors of Al use (European Aluminium Association, 2011). Calculations of $(O(t))$ are undertaken individually for each sector by applying $F(t)s$ with sector-specific average lifetimes. Finally $(O(t))$ from all sectors are summed up in order to derive total old scrap generation. Even though mass balance principle (inflows equal outflows for each year and every process) is fulfilled for the major part of the national material flow system from production to in-use (downstream flows), a mathematically closed mass balance of national secondary production with scrap arising (new, old scrap + scrap trade) is mostly not achieved in dMFMs due to model and parameter uncertainty.

Through adjusting model parameters (e.g. sector-split ratios, average lifetimes, recycling rates) differences between scrap generation and production quantities can be minimised (Pauliuk et al., 2013), but mathematically closed (overall) mass balances are nevertheless hard to obtain. Mainly because of two reasons: 1) Variability of the model parameters is high since precise information on single parameters is hardly available. An individual adjustment through calibration measures is therefore mostly not possible because of lacking information to which extend individual parameters should or might

	Inflow [t/yr]		Outflow [t/yr]																								
Year			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	10		0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07	0,05	0,03	0,02	0,02	0,01
2	10			0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07	0,05	0,03	0,02	0,02
3	10				0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07	0,05	0,03	0,02
4	10					0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07	0,05	0,03
5	10						0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07	0,05
6	10							0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1	0,07
7	10								0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14	0,1
8	10									0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19	0,14
9	10										0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25	0,19
10	10											0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32	0,25
11	10												0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39	0,32
12	10													0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48	0,39
13	10	Input*f(t)													0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57	0,48
14	10															0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66	0,57
15	10																0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74	0,66
16	10																	0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8	0,74
17	10																		0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84	0,8
18	10																			0,2	0,38	0,55	0,68	0,78	0,84	0,86	0,84
19	10																				0,2	0,38	0,55	0,68	0,78	0,84	0,86
20	10																					0,2	0,38	0,55	0,68	0,78	0,84
21	10																						0,2	0,38	0,55	0,68	0,78
22	10																							0,2	0,38	0,55	0,68
23	10																								0,2	0,38	0,55
24	10																									0,2	0,38
25	10																										0,2
		Sum [t/yr]	0,2	0,58	1,13	1,81	2,59	3,43	4,29	5,13	5,93	6,67	7,32	7,89	8,37	8,77	9,08	9,33	9,52	9,66	9,76	9,83	9,89	9,92	9,94	9,96	9,97

Figure 3.2: Graphical calculation scheme of in-use outflows in dMFM. $f(t)$ designates the probability distribution functions of the sector-specific lifetime distribution function $F(t)$ with $(f(t) = F'(t))$

be adjusted. Calibration of parameters without knowledge about the 'real' outflow and stock values could potentially cause implausible model results and thus in most cases predefined sets of parameters are used for optimisation. 2) The convolution of functions for calculating outflows from previous input years would require sophisticated numerical methods for determining optimal parameter values, since all inflows of previous years are of certain relevance when calculating outflows of particular subsequent years.

$$In\,(t),\ In[n] \longrightarrow \boxed{\begin{array}{c} dStock(t) = \big(In(t) - Out(t)\big)\cdot dt = Net(t)\cdot dt \\ Stock[n] + Stock[n-1] = (In[n] - Out[n])\cdot T \\ Stock[N] = Stock[0] + T\cdot \sum_{n=0}^{N}(In[n] - Out[n]) \end{array}} \longrightarrow Out\,(t),\ Out[n]$$

Figure 3.3: Mathematical calculation scheme of in-use stocks in dMFM (Müller et al. (2014))

Besides input-driven models which haven been described in more detail above, also stock-driven models are known from literature (Müller, 2006; Hatayama et al., 2010). In stock-driven models inflows into in-use are not derived from the utilisation and combination of production and trade data, but from an independent estimation of the in-use stock development in each sector. The estimated level of in-use stock corresponds to the material required for fulfilling societal needs of transportation, living, consumption etc. Taking the example of the vehicle stock a practical approach would be considering population, level of motorisation and Al content in vehicles in order to derive estimates on historical and future transportation stock (neglecting other applications e.g. planes, ships etc.). After estimating the trend of the in-use stock development the resulting outflows (old scrap) as well as the required inflows can be calculated.

3.2 Scientific background

3.2.1 Existing dynamic MFA models

Existing studies using the method of MFA can be differentiated by the spatial focus, the covered time period (static vs. dynamic models), model driver (input-driven vs. stock-driven) and with respect to the type of analysis (top-down vs. bottom-up data). In static MFA mostly a single time period is analysed (e.g. one year), it can therefore be considered as a 'snapshot' of a system at a certain point in time (Müller et al., 2014). Static analysis using top-down data have been conducted for global Al flows in 2007 (Cullen and Allwood, 2013; Bertram et al., 2009), providing comprehensive information at a high level of detail for certain flows. Estimates on in-use stocks are not derived from static models using top-down estimates, since only a single time period and thus no accumulation of material is considered. Stock calculations based on bottom-up estimates have been performed for the state of Connecticut (Recalde et al., 2008). But using a bottom-up approach for in-use stock estimates is challenging, since a plurality of inventory data combined with information on average Al content is necessary in order generate a holistic representation of the total in-use stock.

Even though static material flow models provide comprehensive insights into current utilisation of material flows at a usually high level of detail, long-term developments of stocks and scrap flows are mostly not accessible through the analysis of single years. In order to overcome the limitations of static modelling in terms of stock estimations many dMFMs have been developed in recent years. Using historical and current data on material flows within a given system, the accumulation of material in anthropogenic stocks (e.g. vehicles, buildings etc.) can be assessed. Knowledge of existing in-use stocks is of common interest, especially in terms of forecasting the future availability of secondary raw materials, since material will be released from these stocks after use. DMFM have been developed on several geographical scales, besides global models (Liu and Müller, 2013; Hatayama et al., 2009), which mainly focus on global trends and effects of Al use, national models have been developed for a plurality of countries like Germany (Melo, 1999), Italy (Ciacci et al., 2013), Spain (Sevigne-Itoiz et al., 2014), the

U.S. (Chen and Graedel, 2012a; McMillan et al., 2010; Liu et al., 2011), U.K. (Dahlström et al., 2004), Japan (Hatayama et al., 2009) and China (Hatayama et al., 2009; Chen and Shi, 2012). Studies focusing on quality aspects of Al recycling have mostly been conducted for the automobile sector (Modaresi and Müller, 2012; Løvik et al., 2014) and in a first attempt for current and future Al flows in Japan (Hatayama, 2007). Quality aspects in this thesis as well as in the articles refer to alloy composition of Al, nevertheless other aspects of scrap quality (e.g. external contamination, size of scrap etc.) are also of crucial importance for the remelting process. Furthermore MFA studies have often been conducted in order to provide a information basis for LCA-analyses of the Al-life-cycle (McMillan, 2011; Liu et al., 2011; Liu and Müller, 2013).

As a main purpose of dynamic material flow modelling current in-use stocks as well as their historical development have been calculated in order to evaluate secondary resource potential. Existing studies indicate total in-use stocks of 160-410 kg/cap for European countries (Liu and Müller, 2013; Hatayama et al., 2009; Ciacci et al., 2013) and total in-use stocks of 300-520 kg/cap (Chen and Graedel, 2012a; McMillan et al., 2010; Liu et al., 2011) for the U.S. Besides higher Al consumption in the U.S. compared to Europe, the variation in model results is mainly attributed to different choices of parameters. For other parts of the world significant lower in-use stocks are estimated. Taking the example of the BRICS countries Brazil, Russia, India and China, in-use stocks are assessed to be between 10 and 70 kg/cap (Liu and Müller, 2013). Regarding total old scrap a generation potential between 11 and 19 kg/cap (Dahlström et al., 2004; Hatayama et al., 2009; Ciacci et al., 2013) has been calculated for Europe and about 16 kg/cap for the U.S.

An attempt of including quality aspects (types of alloys) into a national dMFM has been conducted for the Al flows in Japan (Hatayama, 2007), analysing the alloying elements silicon (Si), iron, Cu and manganese. By defining 8 categories of Al uses and 16 types of Al alloys the national final Al demand and furthermore current and future old scrap flows divided by alloy type are calculated. In total an increase of recovered scrap by a factor of 2.1 is expected in 2050, with the transport sector being the most dynamic sector in terms of old scrap increase. Comparison and validation of modeled scrap compositions with measurements in the field is difficult, especially with respect to representative scrap sampling.

Comprehensive evaluations of alloy related quality aspects for the transport sector have been conducted by Modaresi and Müller (2012). According to the future use of wrought and cast alloys in cars a potential surplus of cast scrap is identified between

2014 and 2028 depending on separation technologies as well as on the utilisation of secondary castings in automobile industry. Building on this work an even more refined study using a multilayered dMFM has been conducted on the level of different alloys used in various car components (Løvik et al., 2014) of the global automobile fleet. Future demand of primary wrought and cast alloys as well as of secondary wrought and cast alloys is compared with calculated scrap arisings. Since a surplus of scrap, which can not be directly remelted due to alloy composition constraints, is expected by keeping the current practice of car recycling, different interventions on scrap recycling are modeled. With respect to scrap preparation, dismantling and alloy sorting are considered as applicable future technologies. Additionally demagging (removal of magnesium during refining) as well as the use of secondary cast Al in safety relevant car components is considered. The results basically indicated that dismantling as well as alloy sorting will be needed in order to overcome a potential surplus of scrap which can not be directly used due to material composition constraints.

3.2.2 Improvements in dynamic material flow modelling

Integration of bottom-up data

Even though bottom-up approaches could provide detailed insights into flows and material usage of current systems, they are not widely applied yet (Müller et al., 2014). Limited availability and confidentiality of data is an often emerging problem in generating bottom-up models. But, well elaborated bottom-up models could serve as a good basis for adjusting model parameters (sector-split ratios, average lifetimes, Al concentration in final goods etc.) in dynamic top-down models. The combination and complementation of top-down models with bottom-up estimates is an aspect which has hardly been addressed in dMFMs. Especially for models covering large time horizons the calibration and validation of model parameters with external bottom-up estimates is favourable in order to obtain reliable model results. In Paper 1 a static material flow model is developed using bottom-up and top-down estimates. This model is later on used for testing the results and parameters of the input-driven dMFM which has been developed in Paper 2. Additionally the effect of calibrating the dMFM with bottom-up estimates compared to uncalibrated models is shown in Paper 2 (cf. Fig. 4, Paper 2).

Country specific studies

Latest dynamic material flow studies have mainly been conducted on a global or regional level. Even though some national models have been developed, country specific patterns of Al use and scrap utilisation are rarely addressed and analysed in existing studies. In terms of resource management and an optimal recovery and allocation of secondary resources, the interaction between countries as well as country specific patterns of metal (scrap) generation and utilisation are of crucial importance. In regional models trade flows between individual countries could often be a result of (primary) resource availability, unwrought metal demand and generated new and old scrap amounts. With respect to alloy composition and requirements in production, national aspects become increasingly important. These effects are mostly balanced through the market (foreign trade flows) without having a detailed knowledge about the real drivers of these Al flows. Besides comprehensive analyses of Austrian Al flows at a high level of detail, the effect of a varying old scrap ratios in foreign trade flows on the actual old scrap share in secondary production is shown in Paper 1. In Paper 2 the consumption pattern as well as the old scrap generation pattern together with in-use stock development over time is illustrated. Country specific use of Al is further addressed in the additional (not yet published) results of Sec. 5.4, where potential future (mixed) old scrap generation is compared to Austrian production of castings as well as to Austrian final Al demand.

Comprehensive evaluation of uncertainties and sensitivities

A fundamental question regarding uncertainty in dMFMs is, how the uncertainty of model inputs acts on the uncertainty of the outputs. In most cases uncertainty analysis is conducted through Monte Carlo Simulations (MCS) (Liu and Müller, 2013) or Gaussian error propagation (Bader et al., 2011). In such cases potential variations of model results can be quantified for a given uncertainty of model inputs. Besides uncertainty the sensitivity of input parameters becomes of great interest when analysing results from dynamic material flow modelling in more detail. In contrast to uncertainty analysis, which quantifies the uncertainty of model outputs with respect to model inputs, sensitivity analysis provides information about the most relevant input parameters (sector-split ratios, Al concentration in final goods and average lifetimes). Sensitivity analysis in current dMFMs is mostly carried out by uncertainty related 'one-at-a-time' measures. The change of important model outputs is analysed by changing one model input within a certain interval while keeping all other parameters constant. While direct effects of one parameter on model results are thereby investigated, interaction effects, occurring from a simultaneous change of several input parameters, could not be identified. Rigorous methods of sensitivity analysis have hardly been applied to dMFMs so far, except the work from McMillan et al. (2010). Therefore an implementation of global sensitivity analysis to dMFMs seems to be of interest in order to discriminate between first order and higher order sensitivities regarding input parameters. Based on MCS for the most relevant input parameters, the concept of variance-based global sensitivity analysis is applied to results of the dMFM model in Paper 2 using a an algorithm for computing global sensitivity indices (An effective algorithm for computing global sensitivity indices (EASI)) (Plischke, 2010). This represents the first approach of applying the concept of global sensitivity analysis to dMFMs. Besides parameter uncertainties, which constituted the basis for sensitivity analyses, model and scenario uncertainties haven been analysed. Model uncertainties are considered in Paper 2 with respect to initial in-use stock assumptions and material not leaving in-use after average lifetimes due to hibernation or obsolescence. In Paper 3 scenario uncertainties, originating from the uncertainty of future Al demand are analysed and contrasted to parameter uncertainties (sector-split ratios, Al concentration in final goods and average lifetimes) of the historical part of the model. The effect of parameter and scenario uncertainties is evaluated by comparing the cumulative distribution functions (CDFs) of total in-use stock and total old scrap generation.

4 Modelling and analyses

4.1 Static material flow system

For analysing Austrian Al flows a static MFA model of the Austrian system in 2010 is developed in Paper 1 (Fig. 5.1) using the STAN software (STAN, 2013). This model includes the four main stages of the Al lifecycle, namely production and processing, manufacturing, in-use and waste management. Foreign trade flows of unwrought and manufactured metal are considered for the production, processing and manufacturing processes. Additionally the foreign trade of final products (indirect Al flows) is considered in order to finally derive national final Al demand in 2010. For estimating national old scrap generation, which is not available by data, the national scrap market is investigated in a separate process in order to calculate the total old scrap generation from the upstream side. By balancing national secondary production with generated new scrap amounts, foreign trade of scrap and unwrought Al consumption the national old scrap amount is finally derived. In the sub-system of the waste management process (cf. Fig. 4, Paper 1) various routes of scrap processing are evaluated and balanced with the total old scrap amount. In order to derive the scrap amounts originating from the individual in-use sectors, literature data (derived from dynamic models) has been used and applied to the total old scrap flow. From a data perspective the static model represents a combination of top-down and bottom-up estimates. Top-down estimates are used for production and trade data (UN Comtrade, 2014). Bottom-up estimates derived from independent individual data are used for evaluating certain flows especially within the waste management process (separate collected packaging waste, Al waste in MSW, shredded Al scrap etc.).

In order to assess data quality an uncertainty evaluation concept based on a suggested method by Hedbrant and Sörme (2000), Weidema and Wesnaes (1996) and Laner et al. (2014) is applied to the collected data. Through assessing data of each flow using indicators (1, 2, 3, 4) for predefined criteria (e.g. reliability, completeness etc.) finally a coefficient of variance is obtained for every flow (cf. Table 1 and 2, Paper 1) . Applying this method to the given MFA system gives the opportunity to determine uncertainty ranges used in the STAN system in a consistent and transparent way (cf. Table S1, Paper 1).

Besides analysing Austrian Al flows in a very comprehensive way, a first attempt of calculating the shares of different scrap fractions (internal scrap, new (external) scrap, old scrap and net-scrap imports) into national secondary production is carried out within this thesis. A possible range of the old scrap share in secondary production is further shown through altering the new and old scrap ratio in foreign scrap trade (cf. Sec. 4.2, Paper 1). The real share of new and old scrap in imports and exports is not reported and quite often an estimated value in MFA models. In this study it's indicated that the old scrap ratio in national secondary production can vary considerably through altering old and new scrap ratios in imports and exports.

Finally bottom-up stock estimates regarding four in-use sectors (Transport, Building and Infrastructure, Electrical Engineering and Consumer Goods) are conducted (cf. Sec. 2.4, Paper 1). As already mentioned in Sec. 3.2.1, estimating in-use stocks using a bottom-up approach is a challenging task, since in-use stocks are diverse and holistic data is hardly available for any of the in-use sectors. Thus the conducted calculations on in-use stocks should be regarded as a first attempt of calculating national in-use stocks in a bottom-up manner. Al stocks of the individual sectors are certainly subjected to some uncertainty.

4.2 Dynamic material flow system

Even though a detailed view on current Al flows in Austria has been derived from the static model, in-use stocks as well as old scrap flows from different sectors are not direct accessible through static bottom-up modelling. Since the trends of in-use stocks and old scrap generation are of crucial importance for a knowledge-based resource management, a dMFM is developed in Paper 2 capturing Austrian Al flows between 1964 and 2012 (Fig. 4.1). The basic structure complies with the static model in 2010 but some simplifications (especially with respect to sub-systems) have been inevitable due to limitations in historical data availability. The developed model is considered as an input-driven top-down model utilising production data of semi-finished products and all (downstream) trade flows as the main model driver (cf. Sec. 2.1, Paper 2). Model structure and the mathematical routine for calculating in-use stocks and old scrap flows in an input-driven model are described in Sec 3.1. Besides addressing resource management aspects (in-use stock, new and old scrap generation etc.), a special focus is attributed to possible calibration and validation measures of the model (cf. Sec. 2.2, Paper 2). So far dMFMs have been developed on several geographical scales, addressing various aspects of metal flows (Sec. 3.2.1). But calibration of model parameters as well as cross-checking with (external) independent data has usually not been conducted. Within this model calibration of input flows with independent bottom-up estimates has been accomplished for two of the three major sectors of Al consumption (Transport and Packaging). For the Building and Infrastructure sector as the third major sector in terms of Al consumption no independent data for calibration could be identified on a national level and thus for this sector as well as for the remaining sectors, sector-split ratios from literature are adjusted according to the above mentioned calibration. In order to check the consistency and plausibility of the model results several cross-checks of individual stocks and flows (Transport, Electrical Engineering, Building and Infrastructure) as well as cross-checks of the overall balance (e.g. secondary production vs. total scrap arisings) with independent bottom-up estimates are performed (Sec. 2.2, Paper 2). An overview of calibrated and adjusted parameters as well as parameters used for MCS and sensitivity analysis is given in Tab. 4.1. The possibilities of calibration as well as their effect on model trends are clearly illustrated in Paper 2.

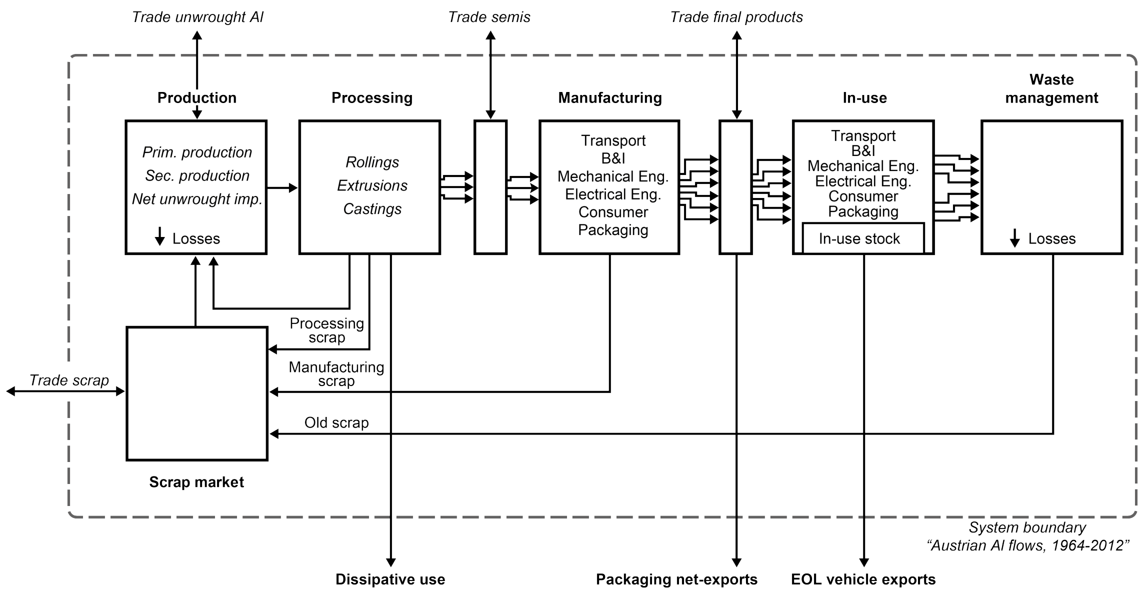


Figure 4.1: System boundary for the historical (data based) part of the model. Based on Fig. 1 in Paper 2.

Uncertainty analysis have been performed for the three most import groups of model parameters (sector-split ratios, average lifetimes and Al content in final goods) using MCS. A number of 1000 model runs is performed using randomly chosen model param-

Table 4.1: Model parameters used for calibration, adjustment, MCS and sensitivity analysis

	Calibrated	Adjusted	MCS	Sensitivity analysis
Sector-split ratios				
Transport	x		x	x
Buildings and Infrastructure		x	x	x
Mechanical Engineering		x	x	x
Electrical Engineering		x	x	x
Consumer		x	x	x
Packaging	x		x	x
Average lifetimes				
Transport		x	x	x
Buildings and Infrastructure			x	x
Mechanical Engineering			x	x
Electrical Engineering			x	x
Consumer			x	x
Packaging			x	x
Al concentration in final goods			x	x

eters sampled from predefined uncertainty intervals. Besides uncertainty evaluations, which especially indicate the variability of the individual in-use stocks with respect to altering model parameters, the concept of variance-based global sensitivity analysis (Saltelli et al., 2008) is applied on the dMFM (cf. Sec. 2.3, Paper 2). Therefore model results from MCS as well as the sampled model parameters are analysed in the EASI algorithm (Plischke, 2010). As a main objective of the sensitivity analysis the contribution of first order effects (the effect of one single (uncertain) parameter on model results) as well as the contribution of higher order effects (the effect of interacting parameters on the model results) should be illustrated.

4.3 Forecasting dynamic material flow system and self-supply evaluations

Based on the above described historical model of Austrian Al flows, which illustrates the trend of in-use stocks and old scrap flows, forecasts on future Al consumption are added to the model in Paper 3, in order to project in-use stock development and old scrap generation until 2050. A reduced system boundary is used for the future part of the model (2013-2050), since final Al demand is directly estimated from current final demand levels (Fig. 4.2). For three of the six in-use sectors (Transport, Buildings and

Infrastructure and Electrical Engineering) a stock-driven (Sec. 3.1) approach is used for estimating future stock development (cf. Sec. Future Consumption Scenarios, Paper 3).

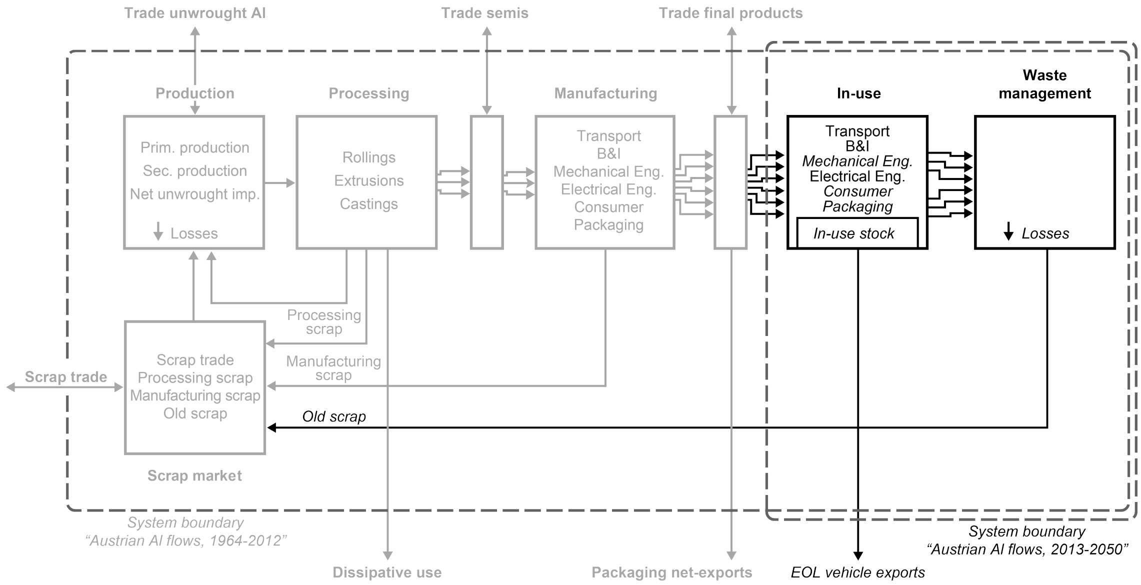


Figure 4.2: System boundaries for the historical and forecasting part of the model. Based on Fig. 1 in Paper 3

Combining existing stocks (derived from the historical, data-driven part of the dMFM) and future development of stocks, inflows and outflows (old scrap) for these three sectors are derived. Generally, the stock-driven approach is considered to be more robust in a long-term perspective than inflow assumptions, since modelling of stocks is associated with some service level needed in society. However, for the packaging sector no stock-driven modelling is possible due to the assumption that major parts of packaging material do not show any accumulation in stocks. For the Mechanical Engineering and the Consumer sector no bottom-up estimates are available, which could be used for stock-driven modelling, thus an input-driven approach is used for the remaining sectors of Mechanical Engineering, Consumer and Packaging. Applying an input-driven approach means, that future development of inflows is estimated based on current consumption levels anticipating a certain increase in annual consumption for the future decades. From the combination of current in-use stocks with estimates on future Al consumption, differentiated by a Low, Middle and High scenario, the future trend of in-use stocks and old scrap generation is calculated.

Addressing the question of future self-supply from secondary Al resources, the calculated future old scrap generation is compared with the expected national unwrought Al consumption, the secondary Al production and the final Al demand. The calculated rate of self-supply provides an indication for future import dependency regarding primary and secondary metal or Al scrap. Additionally to the base case scenario of future self-supply, the effects of enhanced recycling on self-supply are illustrated by altering collection rates of various sectors within the model (cf. Sec. Defining Raw Material Self-Supply, Paper 3).

Finally an uncertainty analysis is conducted, which aims at evaluating the effects of parameter uncertainties originating from the input parameters of the historical part of the model (sector-split ratios, average lifetime, Al concentration in final goods), and scenario uncertainties originating from the indeterminacy of future Al consumption (Low, Middle, High scenarios) (cf. Sec. Evaluation of Uncertainty, Paper 3).

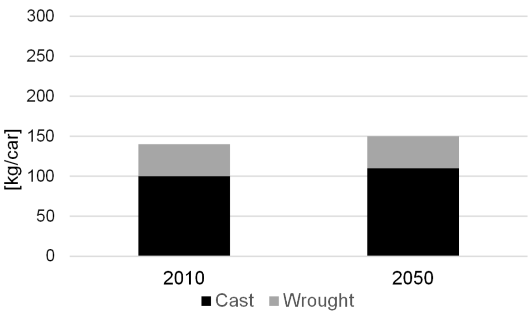
4.4 Quality aspects in national material flow systems

Future old scrap generation as well as self-supply potentials have been analysed up to now mainly from a quantitative point of view, without considering quality aspects like alloy composition. MFA studies including quality issues (Modaresi and Müller, 2012; Løvik et al., 2014) are mostly confined to the Transport sector except one study analysing the Al system in Japan (Hatayama, 2007). The present thesis aims at analysing the established dynamic system of Austrian Al flows with respect to cast and wrought alloys. By dividing past and future old scrap generation into cast and wrought alloys, the effects and consequences on secondary raw material supply are viewed from a qualitative perspective. Since a differentiation by distinct alloys is not possible for European countries due to lacking data, especially with respect to production and trade data, the calculated inflows in the model are divided into wrought and cast alloys using data on domestic (intra-EU) shipments of semi-finished products. In the GARC model (International Aluminium Institute, 2011) European shipment data of semi-finished products are differentiate by rollings, extrusions and castings. Since the main focus of this study is to differentiated between wrought and cast alloys, rollings and extrusions are grouped to one category of wrought alloys.

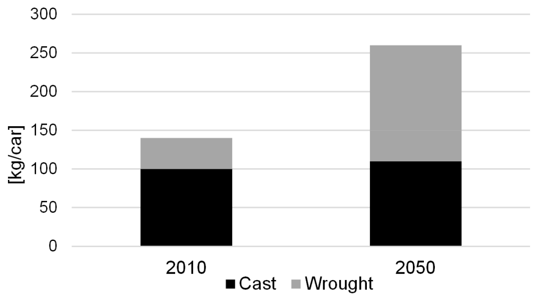
On a global scale castings in the transport sector are considered as the main application of Al cast alloys (Koffler and Florin, 2013). So called 'downcycling' of Al alloys is an often discussed topic, mainly with respect to the open loop recycling of mixed (old) Al scrap from various sectors into cast alloys. But not only regarding cast alloys, recycling of Al is a challenging task in terms of alloy refining. In Table 4.2 the composition of sorted wrought and cast alloy scrap batches as well as the composition of a mixed scrap batch is shown. It can be readily taken from this table, that even sorted scrap fractions could vary considerably in alloy composition. Batch 3 and 4 exhibit higher concentrations in Zn and Cu than batches 1 and 2. Batches 1 and 2 exhibit a possible match to existing alloys 3005, 3104, 3105 and 6061 in contrast to batch 3 and 4. Cast alloys can be easily identified by their high silicon (Si) content and finally from the mix batched it is indicated that direct use of this material could pose difficulties due to the combination of higher Si, Cu and Zinc (Zn) content (Green, 2007).

Even though casting alloys exhibit higher impurity limits than wrought alloys, it appears quite difficult to identify any possibility for direct recycling the listed scrap batches into one of the most common cast and wrought alloys given by the European Aluminium Association ((European Aluminium Association, 2015a), (European Aluminium Association, 2015b)). Since recycling could be limited or at least more costly because of qualitative constraints in utilising mixed scrap fractions, the Austrian system is analysed in terms of wrought and cast alloy recycling. Thereby a special focus is put on the Transport sector as the major consumer of casting alloys and the given current recycling practice of Al scrap (low separation between wrought and cast alloys). Through comparing mix scrap arisings (cast scrap from all sectors plus wrought scrap from the Transport sector) in Austria with national final cast Al demand, a potential surplus of cast and mix scrap fractions over national cast demand is analysed for a closed system. Besides minor dismantling activities no major parts of Al are regularly removed from cars in Austria prior to shredding (Kletzmayr, 2015). Cars are then mostly shredded together with old scrap from other sectors that finally leads to a mixed non-ferrous fraction, which is further processed after shredding. A separation between wrought and cast Al alloys is usually not achieved within the sorting of the non-ferrous shredder fraction. Certainly the considered scenario of directly comparing national scrap generation to final Al demand (closed system) is subjected to some simplifications, especially with respect to real market conditions and international trade, but nevertheless possible quality constraints going along with enhanced domestic recycling and low sorting could be identified.

Concerning the modelled scenarios recycling of future cast and mixed Al scrap is analysed with respect to two crucial parameters: 1) Increasing Al content and changing wrought-cast ratio in cars and 2) improved separation rates in old scrap recycling. Regarding the first parameter two different scenarios are analysed. In the first scenario a slight increase of the cast content from 100 kg/car in 2012 to 110 kg/car in 2050 is assumed while wrought content remains at 40 kg/car (Fig. 4.3a). The second scenario reflects a possible trend of light-weight construction in cars where the wrought content increases from 40 kg/car to 150 kg/car in 2050. Trend in cast content is analogue to



(a) Low scenario of Al content in cars



(b) High scenario of Al content in cars

Figure 4.3: Current and projected Al content in cars with respect to wrought and cast alloys. (a) Assumed scenario of steady Al use in cars; (b) Scenario of high Al content in cars (Modaresi and Müller, 2012)

Table 4.2: Alloy composition of separated wrought and cast scrap (Green, 2007)

Batch	Al	Cu	Fe	Mg	Mn	Si	Zn	Other
Wrought 1	97.1	0.11	0.59	0.82	0.21	0.51	0.45	0.19
Wrought 2	96.7	0.30	0.60	0.60	0.20	0.90	0.50	0.10
Wrought 3	93.1	0.95	1.01	0.89	0.12	2.41	1.25	0.27
Wrought 4	93.1	1.20	0.70	0.70	0.30	2.60	1.20	0.20
Cast 1	83.5	4.40	1.10	0.40	0.30	8.0	1.90	0.40
Cast 2	86.0	3.90	1.00	0.10	0.20	6.30	2.30	0.30
Cast 3	88.4	2.50	0.75	0.58	0.26	5.18	1.27	1.09
Mixed wrought and cast	90.1	2.30	0.80	0.50	0.20	4.50	1.20	0.30

the first scenario (Fig. 4.3b). Concerning wrought and cast separation rates (second parameter) two further scenarios are considered. A 100% mixing of wrought and cast scrap, which corresponds more or less to the current recycling practice in Austria. No separate wrought and cast fractions are assumed after scrap processing in this scenario. In a second scenario only a 10% mixing of scrap fractions is assumed. So, 90% of the whole cast scrap and wrought scrap from the Transport sector are processed to separate scrap fractions and only 10% end up in a mixed scrap fraction. Of course the latter scenario would require additional sorting and processing technologies, which are assumed of being available and are not evaluated from an economic point of view in this study. Combining the scenarios of Al content in cars with the scenarios on scrap separation finally results in four possible model outcomes.

5 Results and discussion

In this chapter the main results of the published articles are summarised. Some additional results which haven't been a part of the published articles are further given. This mainly refers to a separate consideration of residues (dross and skimmings) from the secondary production process in the static model of the year 2010 (Sec. 5.1) and quality specific considerations of future old scrap generation, which have been conducted through an implementation of a wrought and cast alloy differentiation in the dMFM (Sec. 5.4).

5.1 Analysis of the current system

The static material flow system of Austrian Al flows is shown in Fig. 5.1. National secondary Al production in the 2010 budget is around 400 kt, mainly originating from scrap inputs (around 80%) and an unwrought metal content of about 20%. Scrap inputs into national secondary production are mainly consisting of imported scrap (38%), new scrap (30%) and old scrap (13%) based on total production quantities (cf. Fig 5, Paper 1). Al flows associated with generation of process residues like skimmings, dross and salt slag are considered separately in Fig. 5.2, since the budget of 2010 is modelled at the level of goods (Brunner and Rechberger, 2004) without considering specific Al concentrations in various flows. Considering the level of Al specifically for process residues, about 6-7% of total scrap consumption results from dross and skimmings. Salt slags are assumed to be largely exported (3.5 kt/yr), since salt slags are classified as hazardous waste due to the Austrian Waste Register Ordinance (Waste register ordinance, 2008) and because of lacking treatment facilities available in Austria. Nearly 10 kt of dross and skimmings have been generated in 2010, deducing the amount of exports (4 kt) an amount of 5 kt remains as internal scrap. Total generation of dross and skimmings as well as salt slag generation in 2010 is estimated based on a secondary production quantities (Fig. 5.2). An average generation of dross and skimmings of 30 kg/t_{Al} is assumed with 70% metallic Al content. For generated salt slags an Al content of 10% is assumed (Antrekowitsch et al., 2013).

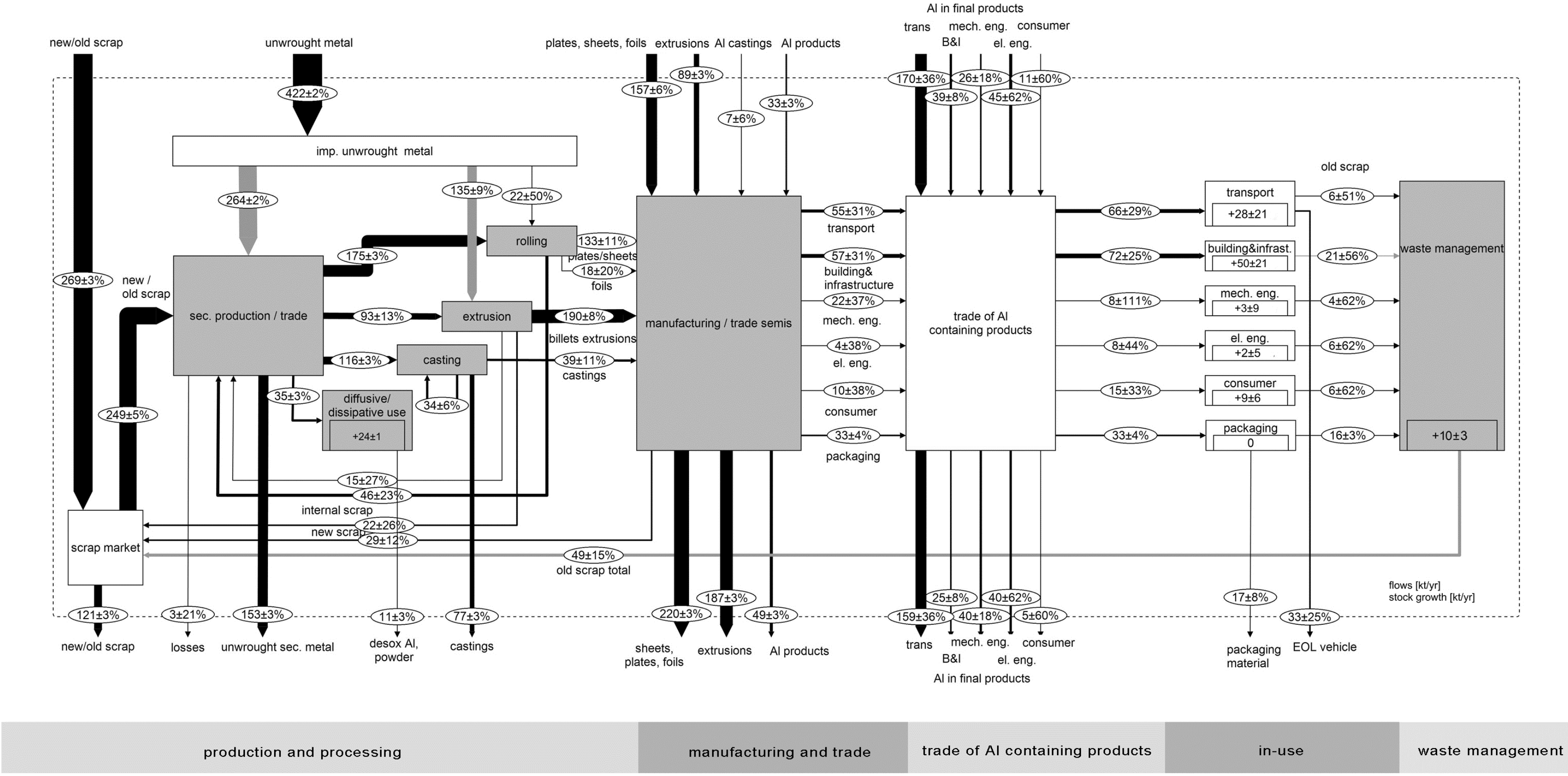


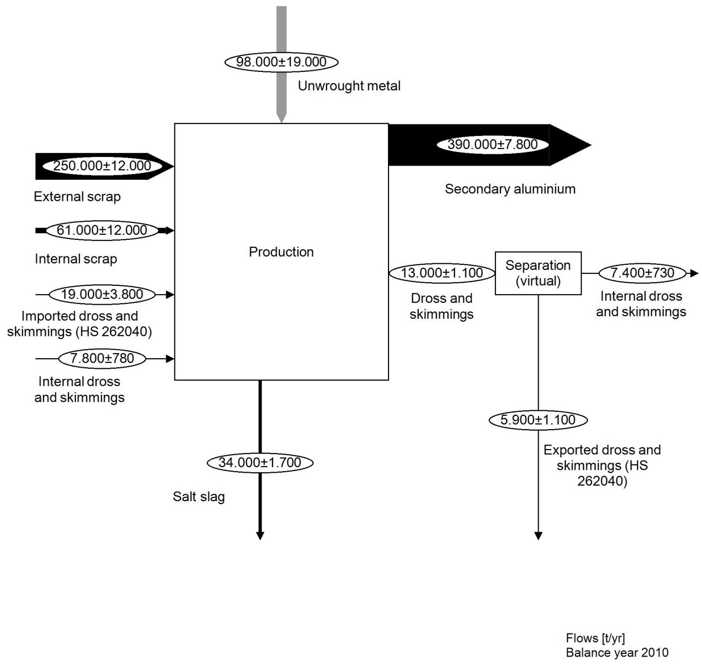
Figure 5.1: Static material flow system of Austrian Al flows in 2010. Based on Fig. 1 in Paper 1

Rolling is the dominating semi fabrication process for nationally produced Al, while Al for extrusion is imported to large extends. Net imports of Al have been evaluated at every stage of the life-cycle and amount to 270 kt/yr at the stage of production, -170 kt/yr at the stage of manufacturing and to 22 kt/yr at the stage of final products. An total amount of around 200 kt/yr is expected to enter national in-use phase, dominated by the Transport (66 kt/yr) and the Building and Infrastructure sector (72 kt/yr). Total increase of in-use stock is calculated being 92 kt/yr which corresponds to 11 kg/yr per capita (cap) (Fig. 5.1). Calculated old scrap generation of around 60 kt/yr is mainly handled through scrap traders (50%), about 16% are shredded and the remaining share is found in separate collection or in municipal solid waste (MSW), which is mechanically or thermally treated. Approximately 10 kt/yr of oxidation, landfill and processing losses are observed in the sub-system of waste management (cf. Fig. 4, Paper 1). Considerable losses of material are also observed through the export of used and end-of-life vehicles (33 kt/yr).

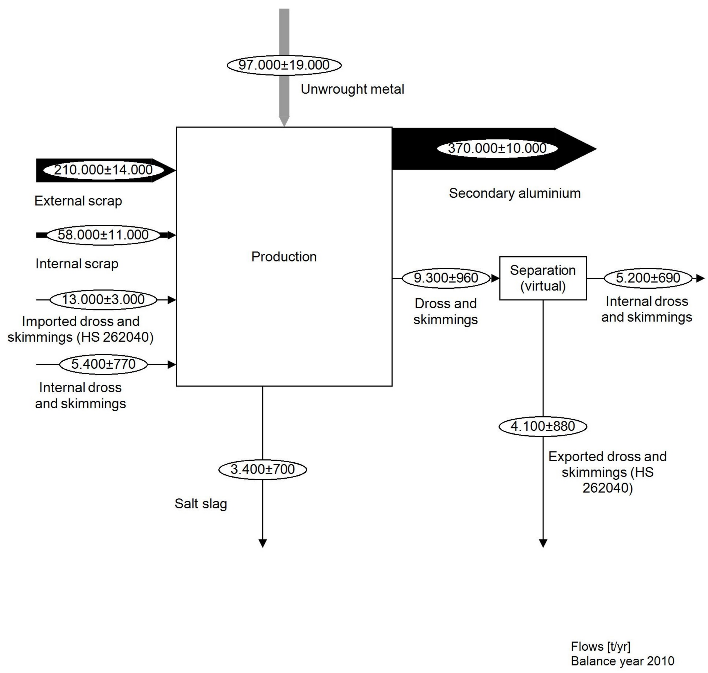
The old scrap ratio (OSR) in secondary production is an important figure in terms of recycling efficiency of a system but it is not available by reported data. Basically the OSR gives the share of old scrap in total secondary production. As Austria represents a quite open system especially with respect to foreign trade of unwrought metal and scrap, the share of old scrap in imports and exports may influence the national OSR considerably. In order to illustrate the variability of the old scrap ratio in secondary production depending on the old to new scrap ratio in scrap trade sample calculations have been conducted considering fixed old to new scrap ratios in foreign scrap trade. According to various compositions of new and old scrap in imports and exports the OSR in secondary production can range between 0% and 66% (cf. Fig. 7, Paper 1). This illustrates the difficulty of determining the apparent old scrap consumption in countries with vital scrap trade, since trade flows are statistically not differentiated concerning new and old scrap shares.

5.2 Historical Al flows and current in-use stocks

The trend of in-use stock development, which is not accessible through static material flow modelling has been calculated using an input-driven dMFM (Sec. 4.2). Besides in-use stock, final Al demand as well as trends in old scrap generation are of great interest for knowledge-based future resource management. An overview on the modelled development of in-use stocks, final Al demand and old scrap generation over the past 30 years is given in Tab. 5.1. Coming from a level of 84 kg/cap total in-use stocks in 1982,



(a) Goods layer



(b) Al layer

Figure 5.2: Flows of Austrian secondary Al production including process residues dross, skimmings and salt slag

Table 5.1: Trends of selected flows and total in-use stocks of the Austrian system

	1982	1992	2002	2012
Unwrought Al consumption [t/yr]	139.000	303.000	377.000	566.000
Net import scrap [t/yr]	14.000	13.000	57.000	158.000
Net import semis [t/yr]	-22.000	-29.000	-50.000	-116.000
Net import final products [t/yr]	-2.000	15.000	26.000	18.000
In-use stock [kg/cap]	94	150	280	360
Final Al demand [kg/cap]	6,9	17	25	25
Old scrap generation [kg/cap]	3,5	6,1	8,8	12

in-use stocks increased up to a level of 360 kg/cap in 2012. Major sectors containing anthropogenic Al are the Building and Infrastructure sector (44%) and the Transport sector (30%). Minor amounts of Al are found in the Engineering sectors (18%) as well as in Consumer Products and re-usable packaging material (8%) (cf. Fig. 2, Paper 2). Over the past 30 years per cap in-use stock increased by a factor of 3.8. At the same time per cap final Al demand increased by a factor of 3.6 up to 25 kg/yr, but a flattening of final Al demand has been observed over the past years also facilitated by the financial crisis in 2008 (cf. Fig. 6, SI Paper 3). Old scrap generation potential increased by a factor of 3.4 over the past 30 years up to 12 kg/cap yr in 2012 (excl. end-of-life vehicle exports and recycling losses) (cf. Fig. 2, Paper 2). The old scrap generation from the dMFM is around 40% higher than old scrap generation in the static model of Paper 1. A proportionally higher growth of final Al demand and in-use stocks compared to old scrap generation indicates that major amounts of consumed Al over the past decades have been used in applications with long average lifetimes.

Switching from the viewpoint of final Al demand to industrial unwrought Al demand it can be noticed, that Al consumption in Austrian industry evolved even more dynamic. Unwrought Al consumption including national production and net-imports of unwrought material increased by a factor of 4 during the past 30 years (cf. Fig. S5, Paper 2). Looking at major trade flows along the value chain of Al it can be seen that net-scrap imports increased tremendously by a factor of 11, which is also a consequence of the shut-down of Austrian primary industry during the nineties of the last century (cf. Fig. S4a, Paper 2). At the same time net-exports of semi-finished products increased by a factor of 5, indicating a vital development of downstream industry in Austria. Regarding indirect Al flows to Austria through the trade of final products, the balance appears quite even over the past decades, being slightly positive with respect to net-imports.

Uncertainty evaluations of the in-use stocks with respect to parameter uncertainty of the three most important groups of parameters (sector-split ratios, average lifetimes and Al concentration in final goods) illustrate, that asymmetric uncertainty intervals are observed due to the chosen Weibull distribution used for the lifetimes. The largest uncertainty interval is observed for the calculated Building and Infrastructure stock, with an uncertainty range of 37% to lower and 12% to higher values relative to the median value (cf. Fig. 2, Paper 2). Besides parameter uncertainties also model uncertainties have been analysed. Model uncertainties arise from a deviation of the model to real life behaviour of the material flow system. In this context two aspects appear to be most influential to model results. Consideration of hibernating and obsolete material no leaving in-use stocks after average product lifetimes and initial stock assumptions, since in-use stocks have presumptively not been equal to zero in 1964. The latter doesn't show a significant effect on in-use stocks and old scrap generation in 2012 (around 1% difference) (cf. Fig. S6c-d, Paper 2). Applying sector-specific rates between 5% and 30% of material not leaving in-use phase to the model, results in a 7% decrease in total old scrap generation and a 5% increase of total in-use stock in 2012 (cf. Fig. S6a-b, Paper 2). Sensitivities are tested applying an available algorithm of variance-based global sensitivity analysis (EASI) to the MCS results of old scrap generation. High direct effects of the sector-split ratios of the packaging sector are observed at the very beginning of the model. Sector-split ratio of the Building and Infrastructure sector also seem to have some direct influence on the results. In total, sector-split ratios seem to have an higher direct influence than average lifetimes (cf. Fig. 5, Paper 2). Negligible effects are observed for the Al concentration in final goods. Since the EASI algorithm has only been applied to parameter inputs of one year together with outputs of the same year, the results should be interpreted as an indication for direct effects in dMFMs. For a total recovery of first and higher order sensitivities a explicit consideration of all parameter inputs of every input year is necessary. Since sensitivity calculation by itself could be depending on sample size (number of individual generated values using MCS) analysing systems like the given one may require considerable computational efforts. An application of global sensitivity analysis to simplified dMFMs seems therefore an appropriate first step for future studies.

5.3 Future in-use stocks, scrap generation and self-supply

Future in-use stock development and old scrap generation is calculated from the combination of the timely resolved current in-use stocks (derived from historical Al flows (cf. Sec. 5.2)) and forecasts on future final Al demand as described in Sec. 4.3. Current total in-use stock of around 3.0 million tonnes (Mt) (360 kg/cap) is expected to increase to 3.9 Mt (440 kg/cap) by 2030 and to 5 Mt (530 kg/cap) by 2050 (cf. Fig. 2a, Paper 3). This corresponds to an increase of total per cap in-use stocks of nearly 50% within the next 40 years. Old scrap generation is calculated from the development of in-use stocks and will increase from a current level of around 130 thousand tonnes (kt) (14 kg/cap) to 210 kt (24 kg/cap) in 2030 and 290 kt (31 kg/cap) in 2050. This corresponds to an increase of total per cap old scrap generation of about 120% (cf. Fig. 2b, Paper 3). Considerable increase in old scrap generation is expected for the Transport and the Building and Infrastructure sector. The increase (factor 3.1) in the Transport sector is strongly depending on the future Al content in cars. Since Al is in an ongoing competition with other materials like high-strength steels, plastics and composite materials (Soo et al., 2015) also used in modern vehicles, uncertainty is inherently attached to the assumption of future Al content in vehicles. From the Building and Infrastructure as well as from the Electrical Eng. sector, future old scrap generation is heavily depending on the chosen average lifetime of products and is expected to increase by a factor of 2.5 in both sectors. For the remaining sectors (Mechanical Eng., Consumer and Packaging) an increase between 1.4 and 3.0 is expected, but since an input-driven approach is used for modelling future final Al demand in these sectors, higher uncertainties have to be taken into account (cf. Fig. 2d, Paper 3).

Taking the ratio of national secondary production with old scrap generation as well as the ratio of final Al demand with old scrap generation, the current and future self-supply (independence from metal and scrap imports) is calculated. Regarding national secondary production self-supply will not exceed 20% by 2050, starting from a today's level of around 15% (cf. Fig. 3b, Paper 3). In case of high demand scenarios (strong increasing secondary production) self-supply can even fall to 10% by 2050. Regarding national final Al demand self-supply has been on an increasing trend, but is currently slowing down and will not exceed a level of 40% by 2050 (cf. Fig. 3a, Paper 3). If enhanced recycling is considered self-supply with respect to final Al demand may increase to a level of 50%. An termination of vehicle exports would increase self-supply further to a level of 74% by 2050 (cf. Fig. 4, Paper 3).

As enhanced recycling of MSW is one major target of European recycling policy (European Commission, 2014b), the proposed future recycling targets for packaging waste are considered in a separate self-supply scenario. As amended in the proposal of the European Commission (European Commission, 2014b) the recycling rates of MSW shall be increase to a minimum of 50% by 2020 and to a minimum of 70% by 2030. Considering the current European average recycling rates of 42% this results in an 28% increase in recycling rates by 2030. An increase of 28% packaging Al recycling in Austria and its effect on self-supply is illustrated in Fig. 5.3. In this figure old scrap generation is related to total unwrought Al consumption (national production + net-imports of unwrought Al). Since total unwrought Al demand (Al consumed for downstream processes like rolling, extrusion and castings) is higher than national production, self-supply of the base case scenario falls below self-supply values of secondary production. A self-supply around 12-13% seems to be realistic with respect to unwrought Al demand. An 28% increase of packaging recycling rates, which is reproduced in the model by an 28% increase of the collection rates in the packaging sector, leads to an increase in self-supply of less than 1%. From a resource management perspective there is hardly any effect to expect from increased recycling of Al packaging waste on national self-supply. Even ambitious recycling targets will affect Al self-supply minimal. Necessary inputs in terms of costs and energy are difficult to estimate for reaching maximum recycling rates and should be taken into consideration when defining future recycling targets. Even though increased recycling of packaging Al appears negligible from a secondary raw material perspective, environmental benefits of enhanced Al recycling have to be considered as well. Since the production of primary Al goes along with high energy consumption (230-340 MJ/kg) (Sverdrup and Ragnarsdottir, 2014) and emissions (e.g. CO_2 15.300 kg/t) (Ding et al., 2012) as well as formation of process residues (e.g. red mud) (Schlesinger, 2014), recycling of Al is environmentally favourable for most recycling scenarios. This indicates that multiple perspectives have to be considered in order to define optimal recycling strategies. In this study only the perspective of secondary raw material supply has been considered.

Parameter uncertainties (originating from the historical part of the model) and scenario uncertainties (originating from the forecasting part of the model) have been compared in order to identify most important assumptions influencing model results of future in-use stock and old scrap generation. While parameter uncertainty (sector-split ratios, Al concentration in final goods and average lifetimes) play a major role for in-use stock development until 2030, the scenario choice becomes more important in the period between 2030 and 2050. Similar characteristics are observed for the total old scrap generation. Parameter uncertainty decreases over time (after 2012), since the average lifetime is the only remaining parameter after 2012 due to the model concept. Old scrap generation in 2050 is therefore mainly determined by the choice of the future consumption scenario (Low, Middle, High), which is indicated by steep cumulative distribution functions (cf. Fig. 5 and Tab. 3, Paper 3).

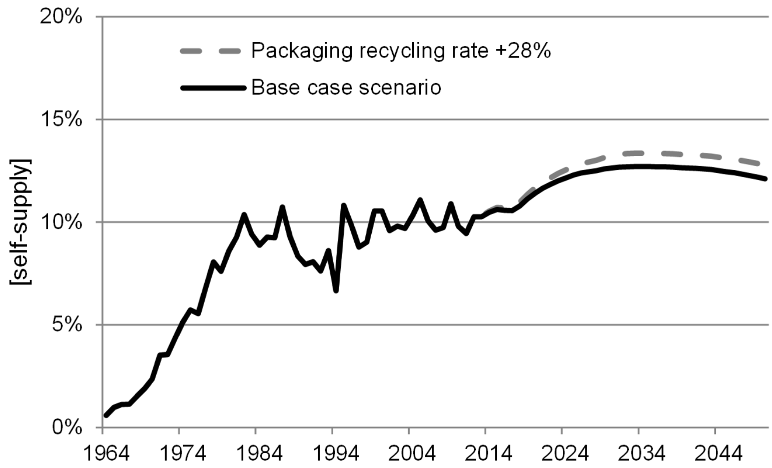


Figure 5.3: Self-supply based on unwrought Al consumption incl. the scenario of increased recycling of packaging waste

5.4 Quality aspects of self-supply evaluations

Calculated (historical) inflows and projected future inflows into in-use phase are taken as the basis for quality evaluations. Modelled inflows into in-use are sub-divided into wrought and cast alloys using shipment data available from the European part of the GARC model. Sector-specific data given in Fig. 5.4 refers to shipments of semi-finished products within Europe. Since Al flows from imports of final products are only around 15% of domestically manufactured products, the given break down is considered as representative for average European consumption and thus applied to the modeled inflows. In the Transport sector cast alloys have ever been dominating over wrought alloys with a share between 70 and 80%. In contrast to the Transport sector Al used in Buildings and Infrastructure is dominated by wrought alloys with a current share of around 90%. Mechanical and Electrical Engineering sector exhibit similar patterns of wrought and cast Al consumption. Starting from historical cast share of approximately 30%, the share of cast alloys decreased over time to a nowadays level of around 10%. Also for the

Consumer sector the share of cast Al is quite low with around 10-20%. For Packaging Material wrought Al is used exclusively.

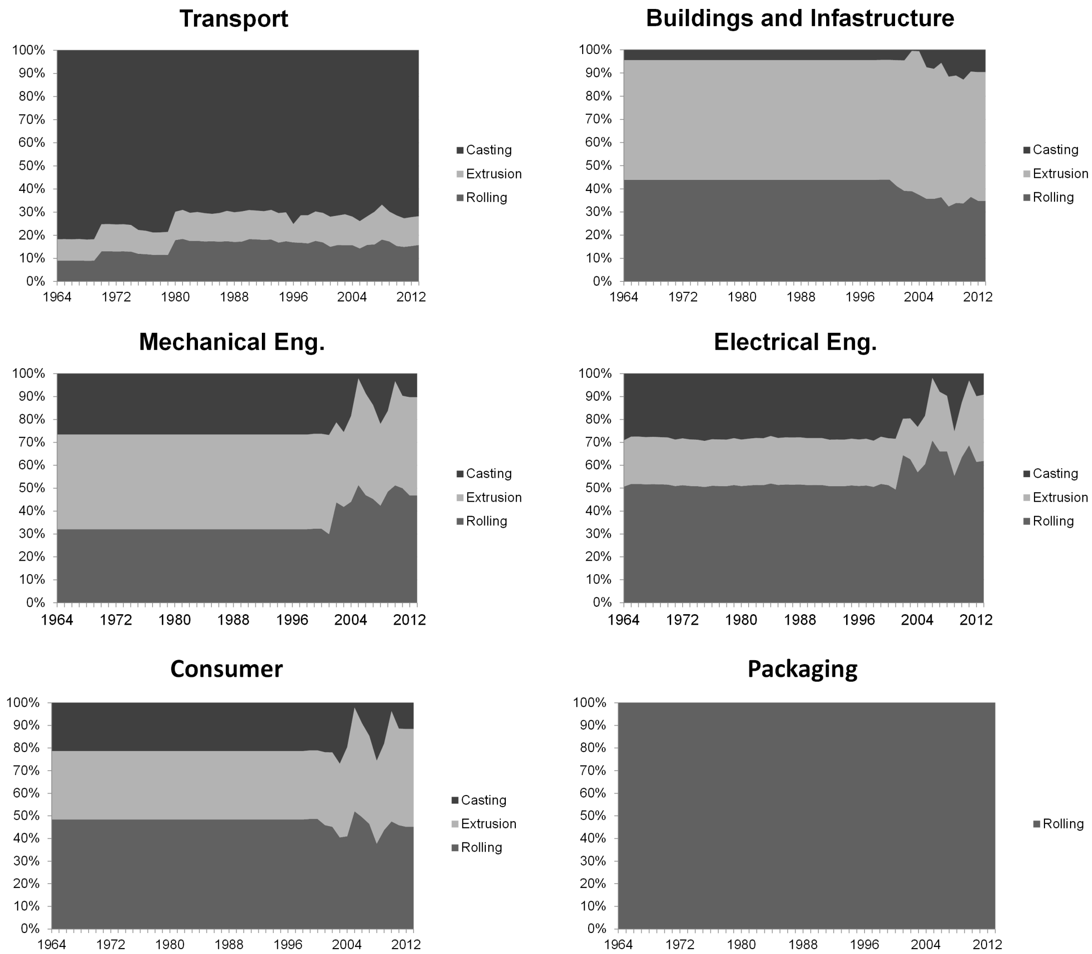
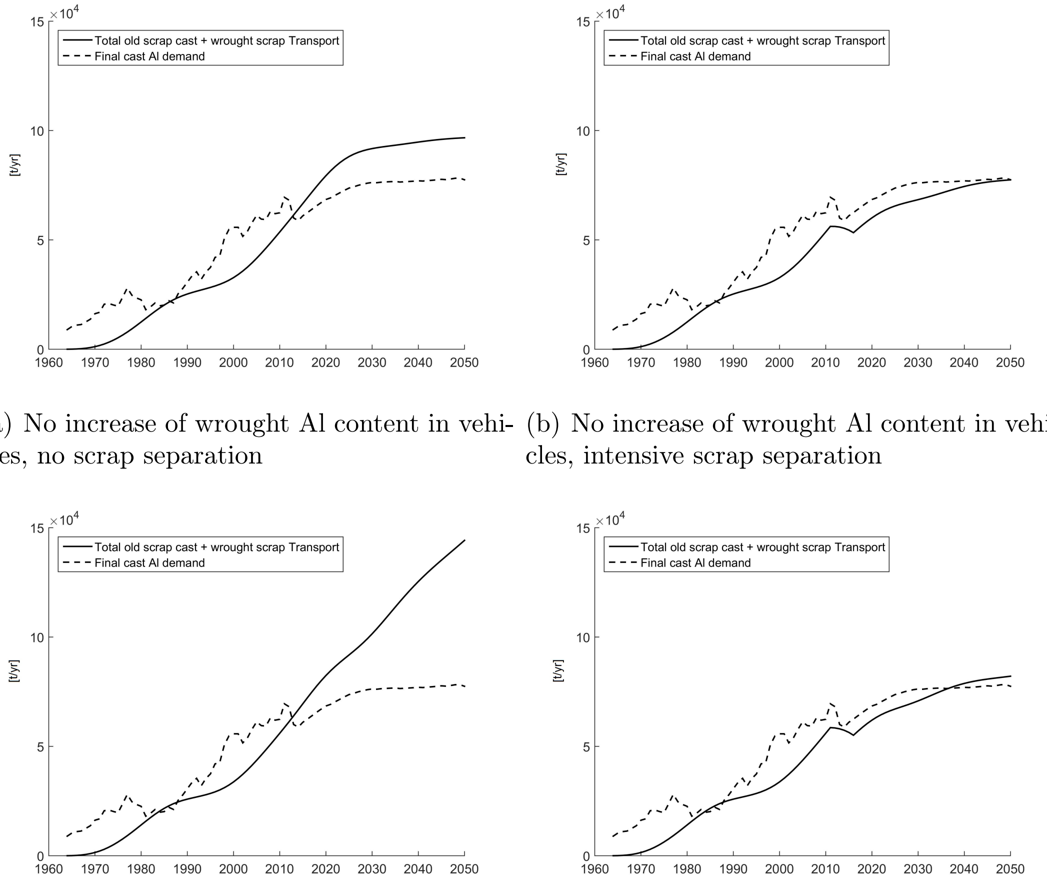


Figure 5.4: Average European wrought and cast Al shares in semis shipments by in-use sectors

In order to analyse possible quality constraints regarding Al recycling in a closed national system (as described in Sec. 4.4), current and future cast and mixed scrap generation is compared to national final cast Al demand (Fig. 5.5). For the scenario of low Al content in vehicles (Fig. 4.3) a surplus of mixed scrap is observed around 2010, if no separation between wrought and cast alloys is applied (Fig. 5.5a). Establishing comprehensive sorting technologies within a period of 5 years (2010-2015) results in a separated cast fraction which matches with final Al demand by 2050 (Fig. 5.5b). For the scenario of high wrought Al use in future vehicles and no separation technology applied in old scrap processing, a distinct surplus of mixed Al scrap compared to national cast



(a) No increase of wrought Al content in vehicles, no scrap separation

(b) No increase of wrought Al content in vehicles, intensive scrap separation

(c) High increase of wrought Al content in vehicles, no scrap separation

(d) High increase of wrought Al content in vehicles, intensive scrap separation

Figure 5.5: Comparison of mixed scrap and separated scrap availability with national final cast Al demand

final Al demand is observed (Fig. 5.5c). Considerable foreign trade flows would be required to balance the misfit between national final demand pattern and the scrap generation pattern in terms of alloy composition. If intensive sorting is applied in this scenario the surplus of mixed scrap over national final Al demand could be retarded to around 2040, but even though intensive sorting is applied a surplus of mixed scrap over final cast demand will be observed after 2040 (Fig. 5.5d).

Additional to national cast final Al demand a comparison of mixed old scrap generation with production quantities of national foundries is carried out. In Fig. 5.6 mixed old scrap generation is illustrated for the two non separation scenarios (taken from Fig. 5.5a, c), together with historical and projected quantities of national foundry production. After 2012 an average annual growth in foundry production of 1% and 2% is assumed.

Comparing mixed scrap generation with foundry metal demand a surplus is not expected, not even for a very moderate growth of 1% per year and the no scrap sorting scenario. However, overall economical and environmental effects of recycling high quantities of wrought alloys into cast alloys are not considered in this analysis. Another assumption is, that national foundries are capable to entirely use scrap as input material, which may not the case for some (safety relevant) products in the automobile industry (Løvik et al., 2014). Further material losses during the casting process are not considered, which may increase input material demand to some extend.

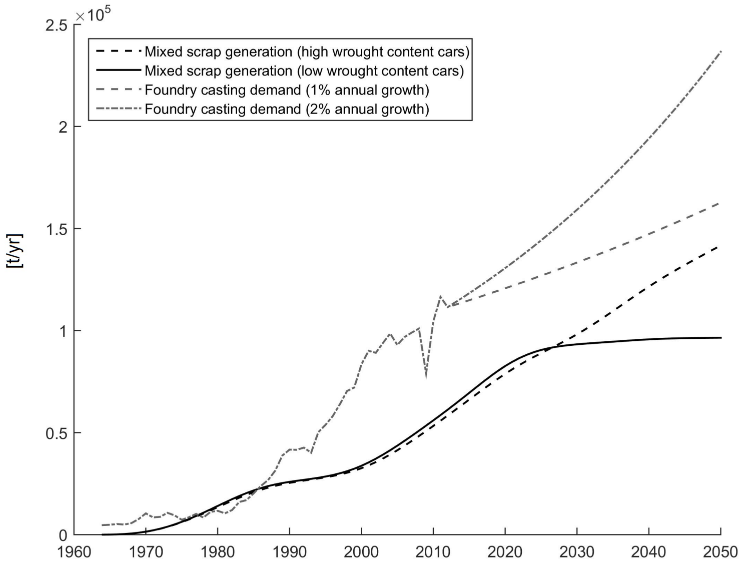


Figure 5.6: Mixed old scrap generation and foundry production quantities

6 Conclusions and outlook

Al stocks and flows and the associated aspects of resource management have been analysed under multiple perspectives in this thesis. A dynamic material flow model for the Austrian system has been developed under the focus of calibrating model inputs and cross-checking model results with external bottom-up estimates. Difficulties in model calibration predominantly originate from the limited availability of bottom-up estimates. Only for the Packaging sector data on annual Al consumption is recorded. Bottom-up studies on average lifetimes of products and the change of product lifetimes of the years are lacking to large extents as well as statistics on material shares and qualities in foreign trade statistics. Nevertheless, calibration and cross-checking of some parts of model could lead to considerable improvement of model results and model trends.

From a resource management perspective, anthropogenic stocks increased considerably over the past decades, which will result in a distinct rise of old scrap generation in coming decades. But, even though old scrap amounts are expected to double (from today's level) by 2050, the potential of increased self-supply is quite limited if consumption of Al is further increasing, even though at smaller growth rates than in past decades. Evaluating self-supply of single countries a clear differentiation between final Al demand and industrial Al demand has to be made. The current Austrian self-supply rate around 30% with respect to final Al demand is estimated to be transferable to other Western European countries, since consumption patterns are presumably similar. In contrast to final Al demand the low self-supply of 15% regarding secondary Al production is a country specific characteristic for Austria. If the continuing growth of national production and downstream industry (strongly driven by exports) is sustained over the next years and decades, the ratio of self-supply could even decrease. Thus, securing the future access to external raw material sources (primary and secondary) will be of crucial importance for the Austrian Al industry.

Evaluations regarding quality aspects of wrought and cast alloys clearly indicated that the current recycling practice will lead to an surplus of mixed Al scrap on a domestic market, if high recycling rates and closed cycles are aspired. Having in mind that Austria is a small country within a global Al market, the results are nevertheless somehow transferable to Europe, since consumption patterns are supposed of being rather similar. This finally indicates that Europe is heading towards a situation where mixed Al scrap fractions may be of limited use in future. Currently, these tendencies are presumably concealed by extensive scrap exports from Europe of about 1.000 kt in 2014, compared to relatively moderate imports of about 360 kt. Alloy compositions of scrap exports are largely not known, which would be an important information in order to evaluate national systems regarding qualities in more detail. Improved recycling and sorting of scrap is a prerequisite for sustainable closed material cycles, but an implementation of such technologies is costly and has to be competitive with international Al markets, which also implies prices of primary Al. International quality standards for secondary raw materials are a key element for facilitating secondary commodity markets (in addition to well established primary commodity markets), since quality and composition are determining material properties to a major extent (Brocklehurst, 2015).

From an environmental perspective the recycling of Al is preferred compared to primary production, due to the reasons mentioned in Sec. 1.3. Nevertheless, negative aspects of Al recycling as the recycling of wrought alloys into cast alloys and the dilution of melted Al scrap with primary Al in order to meet quality requirement are often discussed. Dilution of secondary Al with primary Al increases embodied energy considerably. Adding 25% of primary Al to recycled Al increases embodied energy by a factor of 5 (Cullen and Allwood, 2013) and is therefore not favourable from an environmental perspective in comparison to closed-loop recycling of Al scrap. Whereas the cascading use of Al (recycling of wrought alloys into cast alloys) is not generally environmental disadvantageous, since alternatively primary Al and alloying elements have to be used. This holds as long as (global) demand is still increasing and available scrap amounts are traded and exchanged on an international market. With decreasing growth rates in global Al demand, more ambitious recycling targets and the objective of facilitating regional (e.g. EU) recycling together with increasing recycling content in products, aspects of cascading Al use become more important, since it has to be assured that arisings of high alloyed scrap do not exceed demand for such alloys.

In order to address the above mentioned aspects of secondary raw material use, future studies on dynamic material flow modelling should focus on a regionalisation of models, in optimal case with a resolution at the level of single nations, in order to identify country specific patterns of Al demand and scrap generation as well as to generate information on foreign trade flows between countries. Al flows have been evaluated quite well on a quantitative level on a global scale, but additional information like a differentiation between new and old scrap or wrought and cast alloys is mostly no available from existing models. Qualitative criteria become an increasingly important aspect in pursuing closed regional material cycles (like within the EU) with an optimal utilisation of secondary materials. A matching of regional Al demand, from an industry perspective as well as from an final demand perspective, with available scrap is of fundamental importance for sustainable regional material cycles.

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Appendix

Paper 1

In-depth analysis of aluminium flows in Austria as a basis to increase resource efficiency

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In-depth analysis of aluminum flows in Austria as a basis to increase resource efficiency

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ABSTRACT

Based on the method of material flow analysis (MFA), a static model of Austrian aluminum (Al) flows in 2010 was developed. Extensive data research on Al production, consumption, trade and waste management was conducted and resulted in a detailed model of national Al resources. Data uncertainty was considered in the model based on the application of a rigorous concept for data quality assessment. The model results indicated that the growth of the Austrian "in-use" Al stock amounts to 11 ± 3.1 kg yr^{-1} cap^{-1}. The total "in-use" Al stock was determined using a bottom-up approach, which produced an estimate of 260 kg Al cap^{-1}. Approximately 7 ± 1 kg of Al yr^{-1} cap^{-1} of old scrap was generated in 2010, of which 20% was not recovered because of losses in waste management processes. Quantitatively, approximately 40% of the total scrap input to secondary Al production originated from net imports, highlighting the import dependency of Austrian Al refiners and remelters. Uncertainties in the calculation of recycling indicators for the Austrian Al system with high shares of foreign scrap trade were exemplarily illustrated for the old scrap ratio (OSR) in secondary Al production, resulting in a possible range of OSRs between 0 and 66%. Overall, the detailed MFA in this study provides a basis to identify resource potentials as well as resource losses in the national Al system, and it will serve as a starting point for a dynamic Al model to be developed in the future.

1. Introduction

Because of its manifold material properties (e.g., lightweight, flexibility, corrosion resistance and conductibility) Al is the most widely applied metal after iron (Recalde et al., 2008). Especially with regards to innovative (lightweight) transportation concepts (e.g., electric vehicles and aviation) aiming at the reduction of environmental impacts of public and private mobility, Al is a promising material for breaking the weight spiral (Hirsch, 2011). Despite the fact that Al is the third most abundant element in the Earth's crust (after oxygen and silicon) and known Al reserves (in the form of bauxite ore) will last at least for 200 years at current consumption rates (UNEP, 2011), secondary Al production is becoming increasingly important. In addition to high savings of emissions (e.g., fluorides, perfluorocarbons, polyaromatic hydrocarbons, sulfur dioxide and carbon dioxide) (Moors, 2006), the production of secondary Al only requires 10% of the energy needed for primary production (Quinkertz et al., 2001). Thus, with regard to reducing energy consumption and emissions, facilitating Al recycling would be an adequate approach, however, with the percentage of secondary Al being limited by the ratio of available scrap and total (global) Al demand (Rombach, 2013). Nevertheless, companies in regions with restricted access to primary resources and strict environmental regulations (i.e., the European Union) already depend on the use of Al scrap to a large degree. Against the background of current resource policies, such as those of the European Union, which state that more efficient use of minerals and metals is crucial for heading toward a sustainable closed-loop economy (EU Commission, 2011), the share of secondary metals (including Al scrap) in the production process should further increase in the future.

In numerous research studies aiming to evaluate and improve resource efficiency on a global or national scale, material flow analysis (MFA) has been used (Bertram et al., 2009). This finding also applies also to Al, for which different investigations have been conducted in the last decade. Cullen and Allwood (2013), for instance, recently published their work on global Al flows in 2007, which mainly focused on raising material efficiency in Al production and manufacturing. Milford et al. (2011) further exemplified material

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efficiencies by analyzing production and processing of five different Al products. Dynamic MFA studies of the anthropogenic Al flows have been published for several countries. Chen and Graedel (2012b) presented a study for the U.S., Chen and Shi (2012) for the mainland of China, Dahlström et al. (2004) for the UK, Ciacci et al. (2013) for Italy and Liu and Müller (2013) published a study including 144 countries. Studies focusing specifically on one "in-use" sector have been carried out by Cheah et al. (2009) for the U.S. passenger vehicles and by Mathieux and Brissaud (2010) for commercial vehicles in Europe. In addition to quantitative Al balances, other MFA studies have also focused on material qualities. In Hatayama (2009), the current and future Al scrap flows according to the "in-use" sectors were calculated for Japan, China and the U.S. Hatayama (2007) analyzed the flows of alloying elements in Al goods to determine the maximum recycling rates of Al scraps. Potential limits in Al scrap recycling, especially for end-of-life vehicles, have also been analyzed by Modaresi and Müller (2012) and Løvik et al. (2014). The economic benefits of advanced sorting technologies in Al recycling were presented by Li et al. (2011). Furthermore, the MFA studies conducted provide a database for the calculation of greenhouse gas emissions along the Al life-cycle (Liu et al., 2013; Liu and Müller, 2013; McMillan, 2011). A comprehensive review on dynamic MFA methods to model metal stocks and flows was recently published by Müller et al. (2014).

Although numerous studies on global metal flows have been conducted, a detailed understanding of national material demand as well as consumption and usage patterns on a country level are crucial to evaluate and improve current and future resource efficiencies. Thus, it is the aim of this work to establish the Austrian Al budget for the year 2010 as a basis for anthropogenic resource management. Scrap flows differentiating between old, new and internal scrap are calculated, further a detailed analysis of the waste management system is carried out in order determine recycling efficiency and losses in Al scrap processing in the current system. Finally the "in-use" stock increase is calculated for the given year including considerations of packaging and EOL vehicle exports. Flows at every stage of the Al life-cycle are analyzed at a high level of detail, highlighting data limitations preventing higher resolution of the material flow model. With respect to establishing a national Al resource inventory, this work provides profound insights into how data can be gathered and checked for consistency.

In the first part of this work, the Austrian Al flow model is described in detail, followed by a description of the collection and characterization of MFA data. As many data from different sources with varying quality are integrated into the MFA model, a procedure for the systematic characterization of uncertainty is presented and applied to all material flow data. The resulting Al flows in Austria in 2010 are presented in Sankey style diagrams with special emphasis on Al flows in waste management and domestic secondary Al production. The results are discussed in view of scrap generation data from other European MFA studies and also with respect to determining robust resource efficiency indicators (i.e. recycling ratios) based on the information available about the Al budget. Finally, conclusions about the utility of MFAs on a national level for Al resource management and an outlook on future research activities are provided.

2. Materials and methods

2.1. Material flow analysis (MFA)

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within an arbitrarily complex system defined in space and time (Brunner and Rechberger, 2004). In general, MFA is used to quantitatively characterize the flows of a specific material into, within, and from a system (Chen and Graedel, 2012a). MFA can build on rather simple accounting schemes, static models, or sophisticated dynamic models (van der Voet, 2002), depending on the desired level of mechanistic understanding about material flows within the system to be included in the model. With respect to resource and recycling systems of metals and minerals, MFA has been typically used to connect the sources, the pathways, and the sinks of a material via static or dynamic models (Chen and Graedel, 2012a). Based on the law of the conservation of matter, the results of any MFA can be controlled by a simple material balance comparing all inputs, changes of stocks, and outputs of a process. MFA is performed using an iterative procedure continuously improving the quality of the material flow model and MFA data to arrive at an adequate description of the system.

In this study, the STAN software (Cencic and Rechberger, 2008; TU Vienna, 2013) was used to conduct the MFA, because it is a tailor-made MFA software including routines to consider uncertain quantities of material flows and perform data reconciliation in case of inconsistent input data (free download: www.stan2web.net). Uncertain quantities are expressed by the mean and the standard deviation, assuming a normal distribution (Cencic and Rechberger, 2008). In the case of over-determined systems (more balance equations than unknowns), data reconciliation is used to enforce mass balance constraints on conflicting input data, with quantities having high uncertainty being reconciled more strongly than quantities with low uncertainty (Laner et al., 2014). Subsequently, unknown variables, including their uncertainties, are computed using Gaussian error propagation. In addition, the material flows can be illustrated in Sankey-style diagrams with their width proportional to their value. STAN has been widely used to perform MFA on regional or plant level using models of different sophistication (e.g. Andersen et al., 2011; Dos Santos et al., 2012; Ott and Rechberger, 2012).

2.2. The Austrian aluminum balance

In this study, static MFA modeling (cf. Brunner and Rechberger, 2004) is used to investigate the flows of Aluminum within the geographical border of Austria for the balance year 2010. Only metallic Al flows are considered in this study, ignoring elemental Al contained in many other chemical compounds (e.g., industrial minerals such as kaolinite). Because of the focus on Al on the goods level, the alloying elements of Al are not addressed in this study, notwithstanding the fact that high concentrations of alloying elements could limit Al scrap recycling (Modaresi and Müller, 2012). All numbers given are on the basis of Al content and in 10^3 t (Mg).

In the established material flow model, the Al lifecycle is illustrated using five main stages, namely, production/processing, manufacturing/trade of semis, trade of Al-containing goods, "in-use" phase, and waste management (see Fig. 1). The main direction of Al flows is from production (left) to waste management (right). Imports into the system are presented from top and exports to bottom. As primary Al production in Austria stopped in 1993, production refers to the output of refiners and remelters of the secondary Al industry. The "production" stage represents the melting of secondary Al from scrap and imported unwrought metal.

The "production/trade" stage consists of several individual processes, including secondary production as well as rolling, extrusion and casting. The latter processes allow tracing single processing routes and of the Al related to different semi products. To allocate the flow of imported unwrought metal (potentially including slabs and billets in addition to ingot material for melting) to secondary Al production and processing, a separate process "imp. unwrought metal" is introduced. In addition to the production of semis (rollings, extrusions, and castings), the production of deoxidized Al for the steel industry and Al powders are considered within

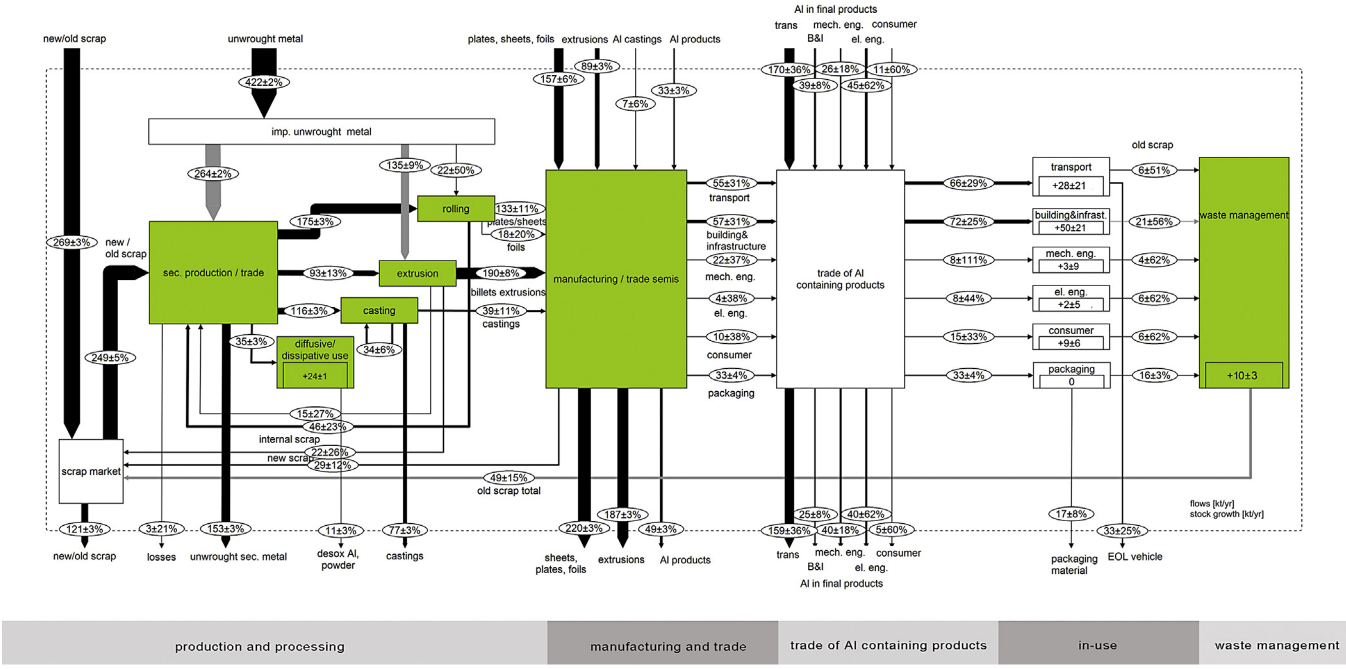

Fig. 1. Aggregated Austrian aluminum balance 2010. Values in kt yr^{-1}. Industrial processes are colored.

the separate process "diffusive and destructive use" including a virtual stock, as Al in these applications is lost to the Al cycle in terms of recovery. The generation of internal scrap is calculated by balancing of inputs and outputs of plants as well as considering material efficiencies for various processing routes. For integrated plants (Al melting and processing), 100% of scrap generation is considered as internal scrap, whereas for processing plants without melting facilities (e.g., extrusion), all of the generated scrap is considered as new scrap. In the process of Al castings, the generated scrap is reused internally. Within the "production/trade" stage, only the trade of unwrought metal is considered.

The "manufacturing/trade" stage considers the balancing of foreign trade of semis and final products. Together with semis from national production, scrap generation from manufacturing of semis is considered and directed to the process "scrap market." The flows of manufactured Al are subdivided to the common end uses of Al: transport, building and infrastructure, mechanical engineering, electrical engineering, consumer products and packaging.

For the foreign trade of final products ("trade of Al-containing products"), a resolution of Al flows to the level of semis is virtually impossible. Thus, Al flows from imports and exports of final products are considered in total for each sector of the "in-use" stage. Imports and exports of Al contained in various final products are obtained by identifying the relevant Standard International Trade Classification (SITC) codes from trade statistics and assigning average Al contents for the different categories. Despite extensive literature research, data about the Al contents of final goods cannot be found for all SITC codes, and thus, some assumptions are inevitable. Further additional uncertainties with regards to the aluminum content originate from the fact that an exact differentiation between products underlying a certain SITC category is hardly possible, especially in terms of materials (e.g., engine blocks from iron or aluminum castings). Thus, high uncertainties are assigned to Al flows associated with the foreign trade of final goods. The flows of "Al in final products" represent the sum of all SITC codes allocated to one end-use category.

The "in-use" stage shows Al inputs and outputs to and from the national "in-use" phase. In addition to old scrap flows from each end use, the exports of end-of-life vehicles (passenger cars and commercial vehicles) as well as the net exports of Al used in packaging of food products are considered separately. The flows of old scrap (=post-consumer scrap) describe obsolete material from the "in-use" sectors. Concerning this old scrap, Al may occur in many different matrices, e.g., as metal parts from building or transportation applications, as integrated part of any machinery or household application, or as packaging waste collected together with municipal solid waste (MSW).

The collection and processing of old scrap is summarized in the waste management stage. Old scrap is recovered via separate collection (i.e., scrap trading) and from the treatment of various end-of-life (EOL) products in incineration, mechanical biological treatment, and shredding. The flows of collected waste electronic and electrical equipment (WEEE), as well as separately collected Al packaging, are presented individually. Losses of Al in waste management mainly occur through oxidation, volatilization during processing and through landfilling of processing residues (e.g., slags and ashes). With the awareness that Al losses also occur at earlier stages in the Al life-cycle (e.g., dissipation in production and "in-use" stage), these losses are not considered explicitly because the focus of this work on resource efficiency. Processed (recoverable) flow of old scrap is directed to the process "scrap trade" representing the national scrap market. The total flow of old scrap indicates the amount of Al old scrap available for secondary production and is directed to the process "scrap market" (Fig. 1). This flow is calculated by balancing the input and output flows of secondary Al production. Imports of net scrap and unwrought metal are based on statistical data. In-house and new scrap is calculated from national production capacities and material efficiencies for different processing routes.

Based on the developed MFA model, a concise breakdown between new, old and in-house scrap is possible. Existing data gaps for a holistic description of national scrap processing in secondary Al production as well as potential improvements in old scrap recovery are further identified. The available data are checked for plausibility, and contradicting statistical data are reconciled to eliminate inconsistencies from the dataset.

2.3. In-use stocks

Existing stocks are evaluated by a bottom-up approach capturing major "in-use" sectors, namely, transport, building and infrastructure, electrical engineering, and consumer products. Bottom-up approaches have been used before (Recalde et al., 2008), but are limited in range, especially for "in-use" sectors with a high diversification of products and little information on inventory from statistics (e.g., consumer goods). However, it is practically impossible to create a complete inventory of the materials present in the stock. Therefore, "in-use" stocks are often investigated using dynamic modeling approaches, applied at the national as well as global levels (Ciacci et al., 2013; Glöser et al., 2013; Hatayama, 2009; Müller et al., 2014). However, a detailed investigation of in-use stocks by means of dynamic systems analysis is not within the scope of this study, as the focus of the analysis is on resource flows. Therefore, the Al stock estimates presented later should be regarded as screening-level results.

2.4. Data collection and characterization

A wide range of data sources are used as inputs for the existing static MFA model. Concerning production and processing of Al goods, production capacities are an essential basis for determining flows. As there is no primary production in Austria, flows of secondary production have to be balanced with inputs from scrap and wrought metal. Al losses within production mainly occur from the generation of dross and salt slags (Boin and Bertram, 2005). Whereas dross is usually further processed by refiners, salt slags are a waste product of the production process and externally processed in recycling plants. As no such national recycling facilities are available, salt slags are exported, which is documented in (BMLFUW, 2011). Al losses are calculated considering average Al content (Tsakiridis, 2012). Losses in filter dust and spent refractory linings are comparatively low (Boin and Bertram, 2005) and thus considered as negligible.

To assess Al flows in different processing routes (e.g., rolling, extrusion, and casting), the national processing capacities are balanced with the input of unwrought metal from national secondary production or imports. The production and processing capacity values are either publicly available (Umweltbundesamt, 2000, 2004) or directly obtained from the stakeholder associations or companies (AMAG, 2012; Austrian Non-Ferrous Metals Federation, 2010; Fachverband der Gießereiindutrie, 2010). All trade data are taken from the foreign trade statistics of Statistik Austria (2010a).

The data for the generation of internal and new scrap are calculated based on the material efficiencies reported in the literature (Aluminium Norf GmbH, 2013; Cullen and Allwood, 2013; Hajeeh, 2013; Hatayama et al., 2012) and checked with input and output balances of the production plants. A differentiation between internal and new scrap is accomplished by distinguishing integrated melting and processing facilities and processing facilities. The data for the import of Al semis and Al goods are taken from foreign trade statistics as well. The distribution of Al semis to different end uses is based on average European figures given by EAA (2005). The distribution data for semis are recorded nationally by Austrian Non-Ferrous Metals Federation (2010). As hardly any data are available on national trade, foreign data from a leading international distributor of steel and metal products is used for allocating domestically traded aluminum goods to various end uses (Kloeckner and Co, 2011).

For the analysis of foreign trade data on Al-containing products, relevant codes from the current SITC classification are selected (Statistik Austria, 2010a). The data on the average Al contents for the different product codes are derived from various data sources, mainly the KEMI database (SCA, 2010). Missing and unobtainable data have been complemented by assumptions that are based on different research studies (Ducker, 2011; Liu and Müller, 2013; Recalde et al., 2008; Salhofer and Tesar, 2011; Troyes, 2009; Truttmann and Rechberger, 2006). Trade data on Al as packaging material were provided by the Austrian packaging recycling association (ARA, 2011). The Al concentration of Al-goods is set to 90%, which is in accordance with (Liu and Müller, 2013).

Although statistics on old scrap collection, processing, trade and remelting are not reported, a detailed description of the subsystem waste management is modeled (Fig. 4). Thus, a comprehensive data study on the individual processing routes was conducted, and subsequently, this information was balanced with the calculated input of domestically generated old scrap in production. Al flow numbers in MSW treatment in incineration and MBTs are derived from previous studies (Rechberger et al., 2010; Skutan and Brunner, 2006; Taverna et al., 2010). Data on Al contents in residues from waste treatment are reported in Mitterbauer and Rechberger (2009). Shredding data are obtained directly from the consortium of Austrian Shredder companies (ARGES, 2012). Reported data on traded aluminum scrap are not available because of non-disclosure policies. Thus, assumptions, based on interviews with major Austrian scrap dealers, have been made (Kranner, 2013; Schaufler, 2013; Scholz, 2013). Data on recycled packaging material and electrical equipment are reported in detail by Altstoff Recycling Austria (ARA, 2011), and the Austrian Coordination Office for Waste Electrical and Electronic Equipment (EAK, 2010). The amount of old scrap from machinery, electrical engineering and consumer application is estimated based on available statistical data (Hatayama, 2009). Data on packaging waste are available from ARA. The flow of Al in old scrap from transportation applications constitutes the amount of Al from transportation applications fed into shredders and disassembled individual components directed to old scrap trade. Though reported data are only available for the Al input to shredders, the amount of Al in components directed to the scrap trade is assumed based on plausibility considerations (i.e., scrap balances). Consequently, the Al flow in old scrap from transportation applications is associated with high uncertainty.

The Al stocks and flows induced by the transport sector are evaluated using official inventory data on different types of vehicle classes (Hirsch, 2011; IPTS, 2008; Statistik Austria, 2010b, 2011b; SCA, 2010; Ducker, 2011; Statistik Austria, 2014). For the building and infrastructure sector, the nationwide area for different types of buildings is calculated and multiplied by their average Al contents (Energie Markt Analyse, 2012; GUA, 2003; Statistik Austria, 2011a; Recalde et al., 2008). The "in-use" stock of electrical engineering represents Al contained in the electrical distribution network (E-Control, 2011). The consumer stock contains all types of electrical and electronic appliances used in households and offices. Data are mainly taken from official inventory statistics of private households (Statistik Austria, 2013). For the public, industry and commercial sectors no inventory data are directly available. Hence, the inventory for these sectors is calculated using secondary data such as the numbers of companies and facilities or workstations (Austria, 2010a,b, 2013; Statistik Austria, 2011a, 2013; WKO, 2012) multiplied by an estimated factor of electrical appliances used.

2.5. Characterization of uncertainty

The present study is characterized by usage of data from various data sources and a detailed explorative data analysis. Data on material flows in this study are derived from a broad range of data sources underlying individual assumptions and generation, with reporting methods for each dataset. Therefore, the consistent characterization of uncertainty in MFA is essential to evaluate the plausibility of material flows and understand the robustness of the model results (Laner et al., 2014). In this study, the uncertainty of

Table 1
Indicators and criteria used to evaluate material flow data quality.

Score	1	2	3	4
Reliability	Systematic (e.g. Statistics Austria) comprehensive and objective data collection	Data collection is documented comprehensively, but was less systematic than for score 1	Hardly any reference data on source and collection method	No references on data source, no documentation of data collection
Completeness	Complete acquisition of data	–	–	Fragmented data
Temporal correlation	Data for the given year	Deviation: 1–5 yr	Deviation: 6–10 yr	Outdated data or no information provided
Geographical correlation	Data for the given area	Data for comparable region/economy/society	Data for less comparable region/economy/society	Data with little geographical correlation or no information given
Expert	Formal Statement; Expert from in the subject of interest	–	–	Assumption; Expert from remotely related subject area

Table 2
Coefficient of variance for the various sensitivity levels and the corresponding indicator scores.

	Sensitivity	1 (%)	2 (%)	3 (%)	4 (%)
Temporal and Geographical correlation	High	0	9	25	50
	Average	0	4	17	41
	Low	0	2	12	30
Reliability		3	9	25	50
Completeness		0	9	25	50
Expert		8	20	40	65

the material flow data is characterized based on an evaluation of the reliability of the data generation method and the representativeness of a datum with respect to the actual quantity of interest (Table 1). The uncertainty evaluation is based on the method suggested by Hedbrant and Sörme (2000) and the data quality indicators put forward by Weidema and Wesnaes (1996) in the pedigree concept. The criteria used to derive scores for the four indicators (reliability, completeness, temporal and geographical correlation) are shown in Table 1.

Reliability of input data relates to the comprehensiveness and systematics of data collection. Institutions with documented and standardized methods of data collection are scored best, while data sources without any documentation on data gathering and without any referencing get the worst score. Classifications in between are used due to the modeller's experience and in relation to other data sources used for the study. For completeness only two distinct scores are predefined, since data are either complete or incomplete. Concerning temporal correlation, the best score is awarded if the year of the reported data matches with the year of interest. For this study two more time intervals of temporal deviation are predefined, 1-5 years and 6-10 years. Data deviating more than 10 years or without temporal reference is scored the worst. Geographical correlation is scored best if Austrian data is provided. Worse scores (2 and 3) are used depending on the economical, societal and structural comparability of the given area with Austria. The worst score (4) is awarded, if no information on area is provided, or no correlation with the Austrian structure is evident. Expert statements are scored 1 or 4, depending on two criteria: the expert's experience in the relevant field, and the information base for deriving the expert estimate.

The evaluation is performed for all material flow data (concentrations, goods, and transfer coefficients) used in the Austrian aluminum flow model. A coefficient of variance is defined for each indicator score, depending on the assigned level of sensitivity (Table 2). In this context, sensitivity describes the influence of a deviation (e.g., temporal or geographical) from the existing datum compared to an ideal datum. Three different levels of sensitivity (sensitive, mid-sensitive and insensitive) are defined for the indicators temporal correlation and geographical correlation, whereas the level for the indicator reliability, completeness, is predefined. With respect to data originating from expert judgment (expert), only one sensitivity level is available. By combining the indicator scores derived from Table 1 and the sensitivity levels given in Table 2 for each material flow datum, the set of coefficients of variance (CV_r, CV_c, CV_t, and CV_g) for calculating the aggregated uncertainty (CV_A) used in the material flow model can be derived. The aggregated uncertainty of the quantity *i* is calculated according to Eq. (1), with $CV_{r,i}$ being the variation coefficient for reliability, $CV_{c,i}$ being the variation coefficient for completeness, $CV_{t,i}$ being the variation coefficient for temporal correlation, $CV_{g,i}$ being the variation coefficient for geographical correlation, and $CV_{A,i}$ being the aggregated variation coefficient expressing the overall uncertainty of quantity *i*. The aggregated uncertainty is defined as the relative standard deviation of a normally distributed variable in the model because all uncertain variables are assumed to be normally distributed in the STAN software, specified by mean value and standard deviation. The methodology used for uncertainty characterization in this study is described in detail, including illustrative examples for the use of the concept in case of various data situations typical for MFA, in a forthcoming study by Feketitsch et al. (2013).

The aforementioned method is used for assessing the uncertainty of Al flows in the balance. The detailed characterization of uncertainties is provided in the Supporting information (SI—first section). In the material flow model Fig. 1 only the sums of Al contained in products of various end uses are shown. The total uncertainties of these flows are calculated from the weighted average of the individual uncertainties of all SITC codes (cf. Supporting information). The Al concentrations in the imported and exported final product categories are assumed to be fully correlated. Therefore, the uncertainty of the exports is directly derived from the uncertainty of the Al contained in imported final products.

$$\sqrt{CV_{r,i}^2 + CV_{c,i}^2 + CV_{t,i}^2 + CV_{g,i}^2} = CV_{A,i} \tag{1}$$

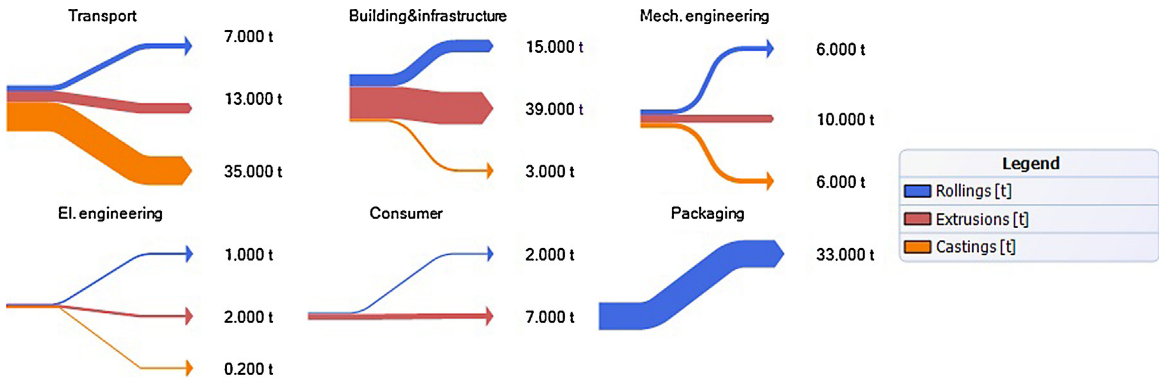

Fig. 2. Breakdown of national production for end-use and semis.

3. Results

3.1. Analysis of the Austrian aluminum balance

Fig. 1 shows the Austrian aluminum budget for 2010. The total production of secondary aluminum amounts to 385,000 t yr^{-1} ± 9%, in 2010 with a total input of aluminum 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 as 61,000 t yr^{-1} ± 36% and for processing plants as 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 calculated. New scrap from the extrusion process is recycled in-house for integrated production plants (15,000 t yr^{-1} ± 2 7%) and partly traded as new scrap on the market in the case of production plants without smelting facility (22,000 t yr^{-1} ± 26%). Approximately 35,000 t yr^{-1} ± 3%, of Al originating from national production and imports of unwrought metal is used for diffusive and dissipative uses. The 24,000 ± 1000 t yr^{-1} of Al additions in stock equates to the national industrial consumption of Al for diffusive and dissipative uses, deducing net exports of powder. Approximately 150,000 t yr^{-1} ± 13% of rolled products are leaving national production, with the foils being 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 that cannot be clearly distinguished from statistics. The total production of castings amounts to 116,000 t yr^{-1} ± 3%, with 66% being exported and 34% being used for national consumption.

The total input into the "in-use" originating manufactured semis from national production and net imports of semis is dominated by the transport (55,000 t yr^{-1} ± 31%) and building and infrastructure sectors (57,000 t yr^{-1} ± 31%). A breakdown of national Al flows into different semi-products is obtained by applying data concerning the average European consumption by "end-use" to the calculated flows (cf. Fig. 2). An Austrian-specific breakdown by end-use sectors (including imports) is available, but only for extrusion (Austrian Non-Ferrous Metals Federation, 2010). For rollings and castings, national production, together with net imports, are allocated to different end uses based on statistics referring to the average situation in Europe (EAA, 2005).

The vast majority (78%) of nationally produced castings are used in transport applications, with 7% being used in building and infrastructure and 14% used in mechanical engineering. More than 55% of extrusions are used in building and infrastructure, approximately 17% are used in transport and 12% in mechanical and electrical engineering. For the national consumption of rolled products, almost half (50%) are used in packaging applications, followed by building and 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. The highest Al flows are observed from trade of goods in transportation applications, although net imports (11,000 t yr^{-1} ± 36%) are comparatively small. The highest Al net imports are due to goods for building and infrastructure applications (14,000 t yr^{-1} ± 8%), and mechanical engineering applications is the only sector with a net export (14,000 t yr^{-1} ± 18%). For electrical engineering and consumer products, a net import is observed (5,000 t yr^{-1} ± 62% and 6.000 t yr^{-1} ± 60%).

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. Transport (66,000 t yr^{-1} ± 29%) and building and infrastructure (72,000 t yr^{-1} ± 25%) exhibit the highest Al inputs. 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 further considered. A total of 60,000 t yr^{-1} ± 13% of Al old scrap entered "waste management" in 2010, which leads to a net stock increase in total "in-use" stock of 92,000 t yr^{-1} ± 26,000 yr^{-1} or 11 ± 3.1 kg cap^{-1}. For reasons of little data availability on the quantities of old scrap generation from "in-use" sectors, the uncertainties of old scrap flows are comparably high. Together with high uncertainties for imports and exports of goods, the "in-use" stock increase is also subjected to high uncertainty. Approximately two-thirds of EOL vehicle exports are attributable to exports of passenger cars, and the remaining share is attributable to export of commercial vehicles and bikes.

3.1.1. Analysis of aluminum stocks

The total Al in use stock amounts to approximately 2,200,000 t or 260 kg cap^{-1}, not including additions of the balance year 2010. Major amounts of the Al stock, approximately 48%, are stored in buildings and infrastructure facilities, followed by 34% in transportation applications, 16% in electrical infrastructure and only approximately 2% in consumer goods (Fig. 3a). A detailed breakdown for different applications in buildings and transportation is shown in Fig. 3b and c. According to Fig. 3c, the major Al amounts (63%) of buildings are contained in industry, commercial and public buildings. Private housing "hosts" approximately one-third of the anthropogenic Al stock in buildings. Analyzing the existing stock of the transportation sector (see Fig. 3d), the significant share of Al stored in cars becomes obvious (74%), and changes in the Al content

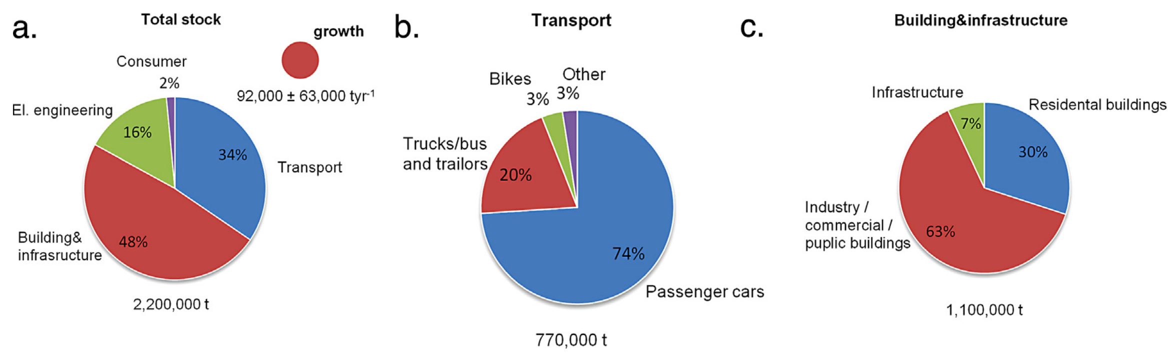

Fig. 3. Breakdown of anthropogenic Al stock. (a) Shows a breakdown of the total stock and the stock increase in 2010 (excluding stock increase of 2010). (b) Shows a breakdown of the transport sector and (c) a breakdown of the building and infrastructure sector.

of cars currently in-use by their production date have been considered (Schäfer, 2012; Ducker, 2011; IPTS, 2008).

3.1.2. *Waste management and old scrap generation*

There are hardly any reported data on old scrap generation and national collection. Nevertheless, flows of Al old scrap from different end uses as well as the flows for different processing routes in waste management have been calculated from the mass balance equations of the material flow model. The total amount of aluminum leaving the "in-use" phase is 60,000 t yr^{-1} ± 13% (10% from transport, 39% building and infrastructure, 6% mechanical engineering, 10% electrical engineering, 10% consumer, and 25% packaging). In Fig. 4, the collection and processing of old Al scrap within the subsystem of the waste management process in Fig. 1 is analyzed in more detail. Quantitatively separate collection and trade of scrap is the most important route for old scrap recycling (59%), followed by shredders (15%) and processing of MSW in incinerators (15%) and mechanical–biological treatment (MBT) (8%). The calculated share of packaging Al and Al scrap input from other end uses in the incineration and MBT process is indicated in Fig. 4. Flows in-between the different processing routes (e.g., shredded Al cans from separate collection) are considered but not shown explicitly for simplification reasons. The recovery of Al from incineration is rather low, with approximately 3% of total input, whereas most of the metal is lost through oxidation and landfilling. Deeper data analyses on Al shares within different processing routes indicate that the main part of Al output from the shredders originates from a mixed input fraction (43%), followed by 20% from packaging material, 15% from consumer electrical goods and 13% from processed cars. At waste incineration and MBT plants, approximately 80% of the Al input originates from packaging material. Approximately 1500 t yr^{-1} of packaging scrap cannot be traced explicitly in our

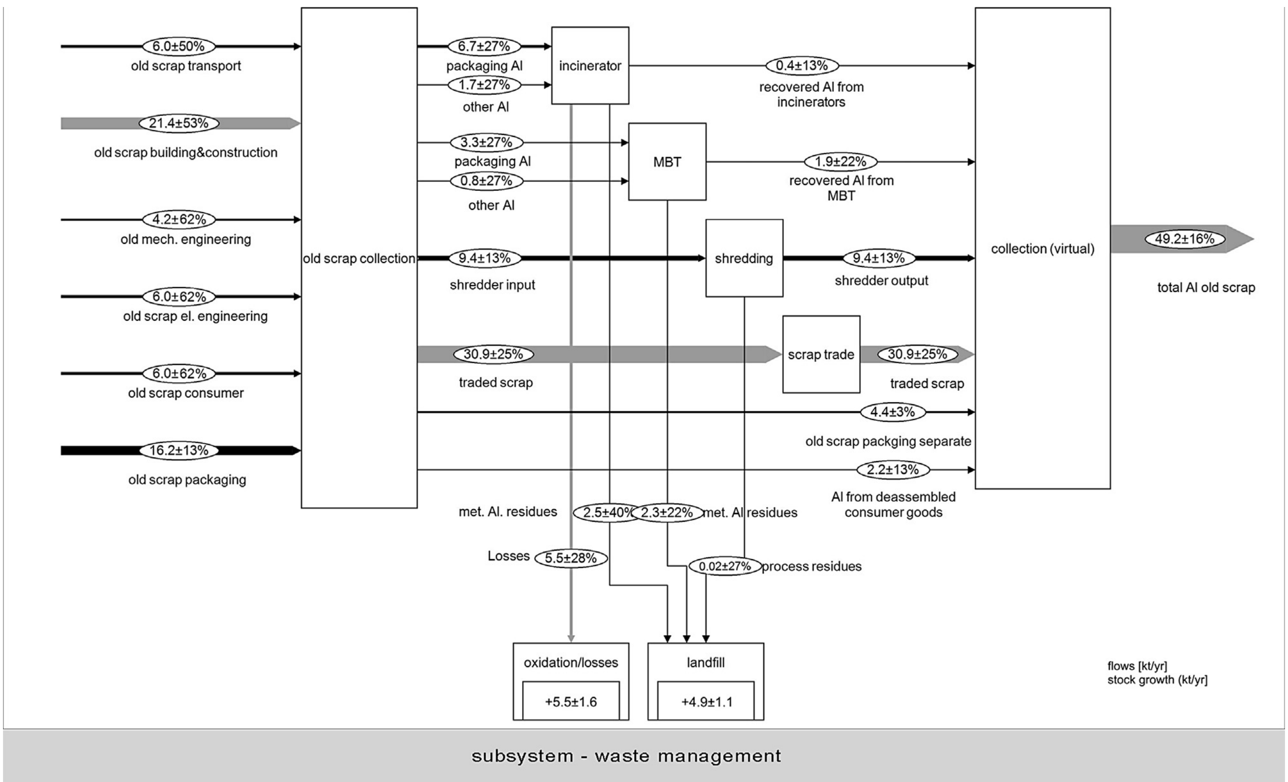

Fig. 4. Subsystem of the waste management process in Fig. 1. Values in kt. (black flows have been derived from data; gray flows have been calculated using the developed MFA model).

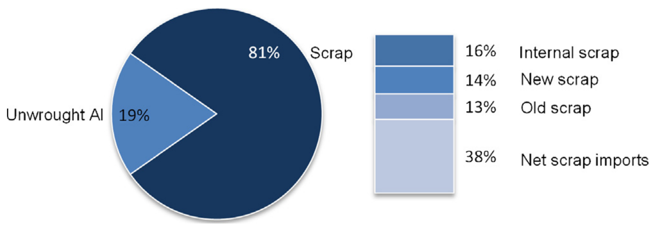

Fig. 5. Calculated scrap share in national secondary Al industry and national scrap generation pattern.

model. Most likely, this amount is subject to informal recycling activities, and thus, it is allocated to the scrap trade route.

3.1.3. Scrap generation and utilization

When balancing of scrap flows with total inputs into secondary Al production, the ratios of each fraction are calculated in the STAN model (cf. Fig. 5). The total input into national secondary Al production consists of 19% unwrought metal and 81% scrap. The share of unalloyed primary metal and Al alloys cannot be specified within the system. Amounting to 38%, imported Al scrap is the highest input fraction in secondary production, followed by 16% of internal scrap and approximately 14% new/old scrap. Within our model, old scrap is fully consumed in production, in the context that a certain share of old scrap is subject to foreign trade flows. However, new and old scrap ratios in foreign trade can't be derived from current statistics, which is, moreover, an important aspect in the calculation of the recycling ratios of the system.

3.1.4. Uncertainty analyses

Analyzing the model from a data perspective reveals that fairly good data are available for the production and processing stage, but the data quality deteriorates along the Al life cycle. Production data are reliable and available from the (Austrian Non-Ferrous Metals Federation, 2010). Import and Export data on unwrought metal and semis are accessible in detail for a broad range of SITC or HS codes. Al flow at the production stage can be assessed within a 3–20% uncertainty range. Nevertheless, for some codes (e.g., unwrought metal), trade flows can hardly be allocated to single processes, as no further information is given other than quantity. Thus, higher uncertainties (14%, 45%) are assigned for the imports of unwrought metal to the rolling and extrusion process. For the splitting of domestically produced semis (except extrusions) and Al goods into different end uses, European data have been used, which results in a higher uncertainty due to imperfect geographical correlation. The overall uncertainty of Al flows at this stage increases to 30–40%.

As in-house and new scrap generation are calculated based on process data and material efficiencies for these processes, the uncertainty of these flows mainly results from missing access to internal process data, imprecise data on efficiencies as well as from the splitting of in-house and new scrap (e.g., scrap treatment within the group). Given that the exact figures about internally recovered scrap could only be quantified with detailed on data on every production facility, these flows are associated with higher uncertainties (25–27%) than externally generated new scrap (7–13%).

In the "in-use" phase, calculation of Al flows originating from foreign trade of final products is interrelated with comparably high uncertainties (59%). For the relevant SITC codes of Al-containing final products, only monetary values and total mass of trade flows are available from statistics. No further information on underlying products as well as material composition of these products can be derived from statistics. High uncertainties in trade flows of Al-containing products subsequently cause high uncertainties in the calculated increase in the anthropogenic stock (±30%). Additional uncertainty arises from minimally documented EOL exports (25%), which can only be considered for the transport sector because of missing data for all other sectors.

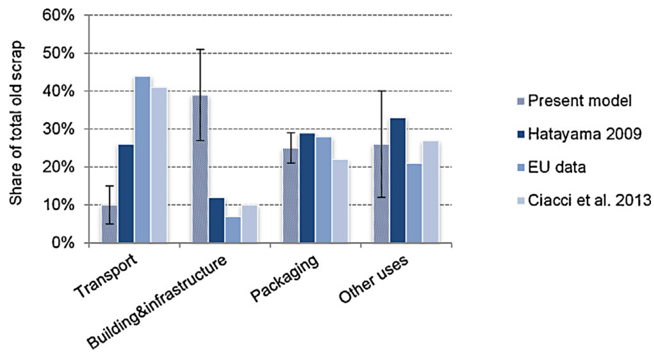

Fig. 6. Breakdown of total old scrap generation. Present model and literature data (Ciacci et al., 2013; Hatayama, 2009; Muchova and Eder, 2010). *Note*: Uncertainties based on total old scrap generation

The total old scrap generation is not documented by any official data. It is thus calculated within the model by balancing the production process (difference of output and known input flows) and can be determined quite well with a small uncertainty range (14%). Scrap flows within the waste management subsystem are calculated using reported data on individual waste treatment processes and are characterized by uncertainties from 3% to 40%, except for old scrap trade and old scrap flow from buildings and infrastructure, which results from balancing with total old scrap flow. An allocation of the total old scrap amount to the "in-use" sectors is only possible for packaging and transport based on reported data, which results in comparably lower uncertainties of these flows (3% and 51%, respectively). For the calculation of the flows from other in-use sectors, secondary data (e.g., from dynamic models) are used to derive the ratios in total scrap generation accordingly. This finally leads to higher uncertainties 62%) on these figures in the model.

In summary, the calculation of Al flows for the "in-use" phase of the Al life cycle in Austria is associated with high uncertainties due to incomplete data on the composition of trade flows and the Al concentrations in final goods. The calculation of the stock increase is currently especially limited by missing/vague data on trade of final goods, EOL exports as well as data of old scrap generation with respect to single "in-use" sectors. However, when data reconciliation is performed on our input data with the STAN software, the mean values of the resulting flows are changed by less than 3% compared with the original (input) values. In addition, data reconciliation results in smaller uncertainties due to constraining the input data based on the mass balance equations defined in the material flow model.

4. Discussion

4.1. Old scrap generation

Static MFA delivers good insight into the analysis of selected flows within the Al system. Especially in waste management, a detailed breakdown of flows regarding both their origin as well as processing route has been obtained. A breakdown of old scrap generation Fig. 6 with regards to their source (sector of end use) has also been determined by applying dynamic MFAs models for Europe (Hatayama, 2009) and Italy (Ciacci et al., 2013) and also by using official EU data (Muchova and Eder, 2010). The total generation rates of old Al scrap reported by these studies are significantly larger (approximately 40 to 60%) than the rates determined within the present work, which could be either due to geographical or methodical differences (dynamic modeling). Old scrap flows in dynamic

Table 3
Old scrap processing efficiency and losses.

Total Al discard	92 kt
EOL vehicle exports	33 kt
Total Al waste generation	59 kt
Total losses	10 kt
Oxidation (incineration)	5.5 kt
Al residues (incineration)	2.5 kt
Al residues (MBT)	2.3 kt
Al residues (shredders)	0.02 kt
Total old scrap	49 kt
Processing rate	83%
Recycling rate	64%

modeling are heavily dependent on (historical) input data and the choice of life-time distribution functions.

The difference in the share of Al scrap from transportation is most likely due to the significant export of EOL vehicles from Austria and other central European countries (Hagelüken et al., 2003), which was not considered in the studies cited in Fig. 6. However, it is important to note that the flow of Al in the exported EOL vehicles is 5 times the flow of Al in old scrap from the transportation sector (cf. Fig. 1). This flow is not available for secondary Al production in Austria, although a substantial part of the vehicles are at the end of their use phase (also abroad). For buildings and infrastructure, dynamic models exhibit lower quantities of old scrap than the static model presented in this work. The discrepancy is potentially caused by incorrect estimates about the lifetime of buildings, as the latter tend to be shorter than expected, especially for modern commercial buildings. This would be in line with a statement of the European Aluminium Association (EAA, 2004), which assumes that major parts of Al old scrap arises from demolished or refurbished commercial buildings. For the packaging sector, the static model is in good accordance with dynamic models. In addition, the results for packaging are associated with small uncertainty due to short lifetimes in dynamic models and a comprehensive database in the static model. For the category “other” uses, no reported data on scrap generation are available, and thus, the static model of the present study is dependent on literature data resulting from dynamic modeling of aluminum systems (Hatayama, 2009).

Besides comparing total scrap generation amounts of this study with studies from other countries, information on national scrap processing efficiency and losses can be derived from the balance. In Table 3 recycling rates and scrap processing rates as well as the losses in the waste management system are given. The recycling rate represents the ratio of Al discarded from in-use (including end of life Al) and the total amount of Al waste entering the waste management system. The processing rate is defined as the ratio between the amount of Al waste generated and the amount of Al old scrap available for remelting.

Main improvements could be made by recovering Al residues from MSW processing routes (incineration, MBT). Since the analyzed data refers to the year 2010, meanwhile some improvements concerning the recovery of Al from incineration residues have been made. Oxidation losses are inevitable in thermal waste treatment and losses from shredding decreased continuously and have already reached a very low level due to sophisticated post shredder technology. Considering the scrap amounts needed in secondary production the leverage for enhanced national supply by improved recovery of Al seems to be very limited at the moment.

4.2. Measuring recycling efficiency

System efficiency measurement involving simply determining recycling ratios is a common procedure. To draw the right conclusions, however, a systematic and comprehensive definition of recycling rates is inevitably required. (Chen, 2013) specified the definitions and calculations for four groups of indicators for the Al system of the United States. One of these groups uses indicators for comparing generation and utilization of new and old scrap. The new to old scrap ratio (NtO SR or OSR) reveals the share of end of life products (=old scrap) used for metal production (secondary aluminum from new scrap: secondary aluminum from old scrap). It could also be expressed as the new scrap ratio (NSR) (aluminum from new scrap: total secondary aluminum produced) or old scrap ratio (OSR) (aluminum from old scrap: total secondary aluminum produced). Another group of indicators specified by Chen (2013) is used for measuring the recycling efficiency at the EOL stage of products. For example, the end of life domestic recycling rate (EOL DRR) indicates the ratio of nationally generated and domestically reused old scrap.

The breakdown of net exports of new and old scrap is a crucial parameter in calculating these indicators. In most cases, scrap composition of imports and exports is assumed based on expert opinion (e.g., all exported scrap regarded as old scrap in Chen, 2013), but for central European countries such as Austria with high amounts of scrap imports and exports (compared to secondary production), such assumptions are impractical for estimating recycling ratios. Assuming 100% exports of generated old scrap would lead to implausible numbers (zero or one) for many indicators (EOL DRR, NtO SR, NSR, and OSR), as exports of scrap clearly exceed national old scrap generation. A differentiation between old and new scrap from statistics is possible only to a limited extent. Based on the subcategories of HS code 7602, the minimum share of new scrap in imports and exports is 20% in 2010. However, the share of new scrap in imports must be higher to satisfy the demand in production for all cases. In addition, the assumption of exporting all of the old scrap generated in Austria is implausible, as there is evidence for national old scrap recycling (e.g., packaging material).

A variation of the share of old scrap exports in relation to total old scrap generation between 25 to 75% results in an EOL DRR between 19 and 57%. For determining new and old scrap ratios (NSR, OSR) (Chen, 2013) in secondary aluminum production, the differentiation between new and old scrap becomes even more important. Especially for countries with comparably high shares of (foreign) traded scrap as input for national production (as it is the case for Austria), the share of net imported and exported old scrap has a high influence on the OSR. According to Chen (2013), the OSR in our example is adapted and calculated by using Formula 2. Based on the results of our model, the importance of differentiating between old and new scrap is demonstrated. Assuming 50% export of national generated old scrap, the OSR can be calculated with respect to varying compositions of foreign traded scrap. In Fig. 7, the OSR is calculated with respect to different compositions of scrap imports and exports. With an import composition of 25% new scrap and 75% old scrap and an export composition of 75% new scrap and 25% old scrap, the OSR is maximum (66%), as the maximum amount of old scrap is imported, and only a little old scrap is exported. The other extreme would be only 25% old scrap in imports (75/25) but 75% of old scrap in exports (75/25), resulting in an OSR of virtually zero. This demonstrates that an indicator such as the OSR is highly dependent on the composition of traded scrap. As long as no better data on composition of traded scrap are available, careful assumptions need to be made, and the application of these indicators needs to be questioned. The composition of traded scrap as well as the share of nationally generated old scrap in exports exhibits a great impact on the calculation of recycling indicators. In view of the calculation of recycling indicators, the uncertainty arising from the unknown composition of imported and exported Al scrap clearly dominates over the effects of the uncertainties associated with

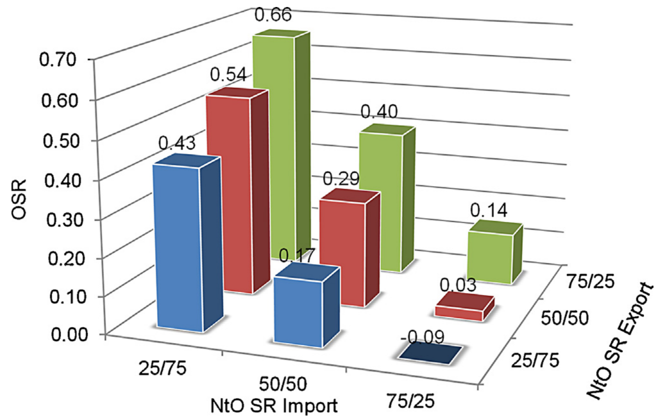

Fig. 7. Relation of old scrap ratio (OSR) to new to old scrap ration (NtO SR) of imports and exports. NtO SR (import, export) is the modeled ratio of old and new scrap in foreign traded scrap (e.g., 25/75 represents 25% of new scrap and 75% of old scrap in foreign traded scrap). OSR (old scrap recycling rate) is calculated according to Formula (2).

the resulting material flows on the derived system performance indicators.

$$\mathrm{OSR} = \frac{(\text{Old Scrap Generation} - \text{Net Export of Old Scrap})}{\text{Net Import of New Scrap} + \text{Net Import of Old Scrap} + \text{Old Scrap Generation} + \text{New Scrap} + \text{Internal Scrap}}$$

4.3. Static modeling of aluminum flows

Static modeling of Al flows is an appropriate tool for a comprehensive description of a national Al budget. Balancing of different data sources in conjunction with plausibility checks allows determining flows not reported or not available (e.g., old scrap). The reliability of the model is high, as major parts of the model are based on reported data with a low level of uncertainty. Inevitable uncertainties due to missing data in some parts of the model (e.g., "in-use" phase) have only local effects on certain calculations (uncertainty of stock increase in specific sectors) and do not affect other parts of the model. With regards to the determination of old scrap generated and especially the breakdown of scrap generation from the different "in-use" sectors, the static model is obviously limited. Although the total amount of old scrap can be calculated from the static model, a breakdown to different end uses is only possible by including imperfect data, which subsequently results in higher uncertainties.

5. Conclusion

Enhancing closed recycling loops is a key element for resource conservation and the reduction of emissions. Thus, increasing knowledge about existing material stocks and flows is an indispensable measure for developing strategies of effective resource management. In this study, a detailed MFA model of the Austrian Al flows in 2010 is established. Flows in production/processing are described with respect to major processing routes of Al (rolling, extrusion, and casting). National consumption of the different Al semis is determined for the major end-use sectors. In addition to foreign trade in Al products, the Al flows associated with the trade of Al-containing final products are considered in the balance. Furthermore, Al flows in waste management are investigated in detail and traced through the various treatment processes. Because of the focus on explorative data analysis within this study, a rigorous concept for assessing material flow data is applied to consider data uncertainty in the model. Detailed data on the production and processing quantities are available, but the level of detail clearly deteriorates for manufacturing, trade of Al-containing products and the waste management sector. Despite the fragmented database, the Al flows for the most important processing routes are determined, and the amounts of traded scraps could be determined based on the developed material flow model in this study.

The outcome of the analyses is a detailed quantification of anthropogenic Al resources in Austria. The total national secondary Al production amounts to approximately 385,000 t, with a total scrap input of 80%. The major parts of the total scrap input originate from net-scrap imports (38%) and from processing and manufacturing scrap (30%). Manufacturing output is mainly driven by transport and building and infrastructure applications. In transportation applications, castings are the dominant products (65%). In building and infrastructure applications, extrusions represent the majority of used semis (68%). Net imports of Al flows from the trade of Al-containing products contribute less than 10% to total Al consumption. Total "in-use" stock growth amounts to $11 \pm 3.1\ \mathrm{kg\,yr^{-1}\,cap^{-1}}$. The generation of old scrap is calculated by analyzing various processing routes of old scrap and balancing the data with data from secondary production. Approximately 7 ± 1 kg of Al $\mathrm{yr^{-1}\,cap^{-1}}$ of old scrap are generated, of which 20% are not recovered due to losses in waste management processes. The highest Al losses in waste management occur in thermal and mechanical processing of MSW, mainly containing Al from packaging waste and consumer goods. In addition to $60{,}000\ \mathrm{t\,yr^{-1}} \pm 13\%$ of old scrap generated, $33{,}000\ \mathrm{t\,yr^{-1}} \pm 25\%$ of Al leave the use phase due to exports of EOL vehicles but are not accounted for as old scrap in this study. The high share of foreign scrap trade and missing information on scrap composition in foreign trade data is problematic with respect to the determination of the national recycling efficiency expressed by the old scrap ratio in secondary production.

From a quantitative point of view, the nationally generated old scrap can supply approximately 25% of total end-use consumption. Including exports of EOL vehicles, this number increases to 40%. However, it should be noted that these numbers are quite theoretical because of neglecting quality aspects in production as well as the market mechanisms of global trade.

The static MFA developed in this study creates a detailed understanding of the patterns of Al use in Austria and therefore enables the identification of major resource potentials as well as resource losses in the system. However, due to the limitations of bottom-up stock estimates in the present model and to make predictions about future resource availability, a dynamic Al flow model will be established. It will combine historical inputs with sector specific life-time functions and collection rates, thus enabling a more comprehensive calculation of old scrap flows and Al stocks in the various end-use sectors. The static model of this study provides essential system understanding for this future endeavor and will also serve as a basis to calibrate the dynamic MFA model.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2014.09.016.

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Supporting information

In-Depth Analysis of Aluminium Flows in Austria as a Basis to increase Resource Efficiency

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Characterisation of uncertainty

The methodology used for uncertainty characterization in this study is described in detail in a forthcoming study by Feketitsch et al. (in preparation). It is based on the method suggested by (Hedbrant and Sörme, 2000) and the data quality indicators put forward by (Weidema and Wesnaes, 1996) in the pedigree concept. Core elements of this system are two evaluation matrices (shown in the paper) for assigning values for the four defined indicators reliability, completeness, temporal correlation, and geographical correlation as well as a sensitivity levels to each datum. Values are individually determined for the existing study as result of the comparison of the collected data sources. For the trade of aluminium (Al) containing final goods the uncertainty of mass flow and Al concentration is assessed individually. Uncertainty data for assessed flow is given in Table S1 of the supporting information.

Table S1 Calculated uncertainties of modelled Al flows

		reliability	completeness	temporal correlation	geographical correlation	
production/trade						**uncertainty**
import	new/old scrap	3%	0%	0%	0%	**3%**
import	unwrought metal	3%	0%	0%	0%	**3%**
import	plates, sheets, foils	3%	0%	0%	0%	**3%**
import	extrusions	3%	0%	0%	0%	**3%**
import	Al castings	9%	0%	0%	0%	**9%**
import	Al products	3%	0%	0%	0%	**3%**
import	cans, containers	3%	0%	0%	0%	**3%**
import	unwrought metal rolling	25%	25%	25%	0%	**43%**
import	unwrought extrusion	25%	25%	0%	0%	**35%**
export	new/old scrap	3%	0%	0%	0%	**3%**
export	unwrought metal	3%	0%	0%	0%	**3%**
export	plates, sheets, foils	3%	9%	2%	0%	**10%**
export	extrusions	3%	0%	0%	0%	**3%**
export	Al castings	3%	9%	0%	0%	**9%**
export	Al products	3%	0%	0%	0%	**3%**
export	cans, containers	8%	0%	0%	0%	**8%**
export	powder	3%	0%	0%	0%	**3%**
export	losses	9%	25%	0%	0%	**27%**
	secondary production	3%	9%	0%	0%	**9%**
	rolling ingot	9%	0%	0%	0%	**9%**
	extrusion ingot	3%	25%	0%	0%	**25%**
	casting ingot, liquid Al	9%	9%	0%	0%	**13%**
	desoxidation and unwrought Al	9%	9%	0%	0%	**13%**
	internal scrap rolling	9%	25%	0%	0%	**27%**
	internal scrap extrusion	9%	25%	0%	0%	**27%**
	internal scrap casting	9%	25%	0%	0%	**27%**

Table S1 continued

	plates, sheets	9%	9%	0%	0%	**13%**
	foils					**20%**
	billets/extrusions	9%	9%	0%	0%	**13%**
	castings	9%	25%	0%	0%	**27%**
manufacturing/trade						
import	plates, sheets, foils	3%	0%	0%	0%	**3%**
import	extrusions	3%	0%	0%	0%	**3%**
import	Al castings	3%	0%	0%	0%	**3%**
import	Al products	3%	0%	0%	0%	**3%**
import	containers, cans	3%	0%	0%	0%	**3%**
export	plates, sheets, foils	3%	0%	0%	0%	**3%**
export	extrusions	3%	0%	0%	0%	**3%**
export	Al castings	3%	0%	0%	0%	**3%**
export	Al products	3%	0%	0%	0%	**3%**
export	containers, cans	3%	0%	0%	0%	**3%**
TC	rolling by end use	9%	9%	2%	17%	**21%**
TC	extrusions by end use	3%	0%	0%	0%	**3%**
TC	castings by end use	3%	9%	0%	0%	**9%**
TC	trade to end uses	25%	50%	0%	2%	**56%**
TC	new scrap generation manufacture of foils	9%	3%	0%	2%	**13%**
TC	new scrap manufacture of rollings	9%	25%	0%	2%	**27%**
TC	new scrap generation manufacture of extrusions	9%	25%	0%	2%	**27%**

Table S1 continued

trade of Al containing products						
Quantity						
Transport						
SITC rev. 4	712	3%	0%	0%	0%	**3%**
SITC rev. 4	713	3%	0%	0%	0%	**3%**
SITC rev. 4	714	3%	0%	0%	0%	**3%**
SITC rev. 4	716	3%	0%	0%	0%	**3%**
SITC rev. 4	718	3%	0%	0%	0%	**3%**
SITC rev. 4	781	3%	0%	0%	0%	**3%**
SITC rev. 4	782	3%	0%	0%	0%	**3%**
SITC rev. 4	783	3%	0%	0%	0%	**3%**
SITC rev. 4	784	3%	0%	0%	0%	**3%**
SITC rev. 4	785	3%	0%	0%	0%	**3%**
SITC rev. 4	786	3%	0%	0%	0%	**3%**
SITC rev. 4	791	3%	0%	0%	0%	**3%**
SITC rev. 4	792	3%	0%	0%	0%	**3%**
SITC rev. 4	793	3%	0%	0%	0%	**3%**
Building&Infrastructure						
SITC rev. 4	69121	3%	0%	0%	0%	**3%**
SITC rev. 4	69129	3%	0%	0%	0%	**3%**
Mechanical engineering						
SITC rev. 4	721	3%	0%	0%	0%	**3%**
SITC rev. 4	722	3%	0%	0%	0%	**3%**
SITC rev. 4	723	3%	0%	0%	0%	**3%**
SITC rev. 4	724	3%	0%	0%	0%	**3%**
SITC rev. 4	725	3%	0%	0%	0%	**3%**
SITC rev. 4	726	3%	0%	0%	0%	**3%**
SITC rev. 4	727	3%	0%	0%	0%	**3%**

Table S1 continued

SITC rev. 4	728	3%	0%	0%	0%	**3%**
SITC rev. 4	731	3%	0%	0%	0%	**3%**
SITC rev. 4	733	3%	0%	0%	0%	**3%**
SITC rev. 4	735	3%	0%	0%	0%	**3%**
SITC rev. 4	737	3%	0%	0%	0%	**3%**
SITC rev. 4	741	3%	0%	0%	0%	**3%**
SITC rev. 4	742	3%	0%	0%	0%	**3%**
SITC rev. 4	743	3%	0%	0%	0%	**3%**
SITC rev. 4	744	3%	0%	0%	0%	**3%**
SITC rev. 4	745	3%	0%	0%	0%	**3%**
SITC rev. 4	748	3%	0%	0%	0%	**3%**
SITC rev. 4	69212	3%	0%	0%	0%	**3%**
SITC rev. 4	69242	3%	0%	0%	0%	**3%**
SITC rev. 4	69244	3%	0%	0%	0%	**3%**
SITC rev. 4	69313	3%	0%	0%	0%	**3%**
SITC rev. 4	69440	3%	0%	0%	0%	**3%**
Consumer Products						
SITC rev. 4	761	3%	0%	0%	0%	**3%**
SITC rev. 4	762	3%	0%	0%	0%	**3%**
SITC rev. 4	763	3%	0%	0%	0%	**3%**
SITC rev. 4	764	3%	0%	0%	0%	**3%**
SITC rev. 4	775	3%	0%	0%	0%	**3%**
			0%	0%	0%	**3%**
SITC rev. 4	69743	3%	0%	0%	0%	**3%**
SITC rev. 4	69753	3%	0%	0%	0%	**3%**
						3%
SITC rev. 4	751	3%	0%	0%	0%	**3%**
SITC rev. 4	752	3%	0%	0%	0%	**3%**
SITC rev. 4	759	3%	0%	0%	0%	**3%**
SITC rev. 4						

Table S1 continued

Electrical Engineering							
SITC rev. 4	771		3%	0%	0%	0%	**3%**
SITC rev. 4	772		3%	0%	0%	0%	**3%**
SITC rev. 4	773		3%	0%	0%	0%	**3%**
SITC rev. 4	77316		3%	0%	0%	0%	**3%**
SITC rev. 4	77317		3%	0%	0%	0%	**3%**
SITC rev. 4	774		3%	0%	0%	0%	**3%**
SITC rev. 4	776		3%	0%	0%	0%	**3%**
SITC rev. 4	778		3%	0%	0%	0%	**3%**

trade of Al containing products

Concentration		Source	reliability	completeness	temporal correlation	geographical correlation	
Transport							
SITC rev. 4	712	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	713	BMW	25%	50%	9%	0%	**57%**
SITC rev. 4	714	estimate based on 713	25%	50%	9%	0%	**57%**
SITC rev. 4	716	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	718	estimate based on 716	25%	50%	0%	0%	**56%**
SITC rev. 4	781	Ducker	9%	9%	0%	0%	**13%**
SITC rev. 4	782	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	783	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	784	estimate based on 713	25%	50%	0%	0%	**56%**
SITC rev. 4	785	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	786	EAA	9%	9%	0%	0%	**13%**
SITC rev. 4	791	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	792	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	793	KEMI	25%	25%	0%	0%	**35%**
Building&Infrastructure							
SITC rev. 4	69121	estimate.	8%				**8%**

Table S1 continued

SITC rev. 4	69129	estimate	8%				**8%**
Mechanical engineering							
SITC rev. 4	721	Graedel, KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	722	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	723	Graedel	25%	25%	0%	25%	**43%**
SITC rev. 4	724	Graedl, KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	725	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	726	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	727	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	728	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	731	estimate based on 725, 726, 727	25%	50%	0%	0%	**56%**
SITC rev. 4	733	Graedel	25%	25%	0%	25%	**43%**
SITC rev. 4	735	Graedel	25%	25%	0%	25%	**43%**
SITC rev. 4	737	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	741	estimate	25%	25%	0%	0%	**35%**
SITC rev. 4	742	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	743	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	744	KEMI	25%	25%	0%	0%	**35%**
SITC rev. 4	745	estimate based on 725, 726, 727, 737	25%	50%	0%	0%	**56%**
SITC rev. 4	748	estimate	25%	50%	0%	0%	**56%**
SITC rev. 4	749	estimate	25%	50%	0%	0%	**56%**
SITC rev. 4	69212	estimate	8%				**8%**
SITC rev. 4	69242	estimate	8%				**8%**
SITC rev. 4	69244	estimate	8%				**8%**
SITC rev. 4	69313	estimate	8%				**8%**
SITC rev. 4	69440	estimate	8%				**8%**

Table S1 continued

Consumer Products							
SITC rev. 4	761	(Truttmann and Rechberger, 2006)	9%	25%	0%	0%	**27%**
SITC rev. 4	762	(Truttmann and Rechberger, 2006)	9%	25%	0%	0%	**27%**
SITC rev. 4	763	(Truttmann and Rechberger, 2006)	9%	25%	0%	0%	**27%**
SITC rev. 4	764	(Truttmann and Rechberger, 2006)	9%	25%	0%	0%	**27%**
SITC rev. 4	775	(Salhofer and Tesar, 2011, Truttmann and Rechberger, 2006), Salhofer, KEMI (SCA, 2010)	9%	25%	0%	0%	**27%**
SITC rev. 4	69743		8%				**8%**
SITC rev. 4	69753		8%				**8%**
SITC rev. 4	751	Truttmann and Rechberger 2006, SCA 2010, Salhofer and Tesar 2011)	9%	25%	0%	0%	**27%**
SITC rev. 4	752	Truttmann and Rechberger 2006, SCA 2010, Salhofer and Tesar 2011)	9%	25%	0%	0%	**27%**
SITC rev. 4	759	Truttmann and Rechberger 2006, SCA 2010, Salhofer and Tesar 2011)(Salhofer and Tesar, 2011, SCA, 2010, Truttmann and Rechberger, 2006)	9%	25%	0%	0%	**27%**
SITC rev. 4							
Electrical Engineering							
SITC rev. 4	771	KEMI (SCA, 2010)	25%	25%	0%	0%	**35%**
SITC rev. 4	772	estimate based on 771	25%	50%	0%	0%	**56%**
SITC rev. 4	773	estimate based on 771	25%	50%	0%	0%	**56%**
SITC rev. 4	77316	(Centrovox, 2013) (Prysmian, 2013)	25%	50%	0%	0%	**56%**
SITC rev. 4	77317	(Centrovox, 2013, Prysmian, 2013)	25%	50%	0%	0%	**56%**
SITC rev. 4	774	estimate based on 763, 752	25%	50%	0%	0%	**56%**
SITC rev. 4	776	estimate based on 763, 753	25%	50%	0%	0%	**56%**
SITC rev. 4	778	estimate based on 763, 754	25%	50%	0%	0%	**56%**
In-Use							
export	final goods packaging		3%	9%	0%	0%	**9%**
export	final goods EOL vehicle		3%	25%	0%	0%	**25%**

Table S1 continued

	nat. input tranport		9%	25%	25%	12%	**38%**
	nat. input building&infrastructure		9%	25%	25%	12%	**38%**
	nat. input mech. engineering		9%	25%	25%	12%	**38%**
	nat. input el. engineering		9%	25%	25%	12%	**38%**
	nat. input consumer		9%	25%	25%	12%	**38%**
	nat. input packaging		9%	25%	25%	12%	**38%**
	old scrap transport		9%	50%	0%	0%	**51%**
	old scrap building&infrastructure						
	old scrap mech. Engineering		25%	50%	9%	25%	**62%**
	old scrap el. Engineering		25%	50%	9%	25%	**62%**
	old scrap consumer		25%	50%	9%	25%	**62%**
	old scrap packaging	(ARA, 2013)	3%	0%	0%	0%	**3%**
Waste Management							
	packaging Al incineration	(BMLFUW, 2011)	9%	25%	0%	0%	**27%**
	other Al incineration	(BMLFUW, 2011)	9%	25%	0%	0%	**27%**
	packaging Al MBT	(BMLFUW, 2011)	9%	25%	0%	0%	**27%**
	other Al MBT	(BMLFUW, 2011)	9%	25%	0%	0%	**27%**
	Al shredder Input	(ARGE, 2012)	9%	9%	0%	0%	**13%**
	packaging Al separate collection	(ARA, 2013)	3%	0%	0%	0%	**3%**
	disassembled consumer goods	(EAK, 2010)	9%	9%	0%	0%	**13%**
	met Al residues shredder	(ARGE, 2012)	9%	25%	0%	0%	**27%**
	recovered Al from incinerators	(MA 48, 2013)	9%	9%	0%	0%	**13%**

Input data of the balance

The underlying data as well as important model parameters of the Austrian Aluminium Balance in Fig. 1 and the waste management subsystem is given in Table S2. For external calculated flows, considered data and parameters are referenced in order to enhance the traceability of the system. The difference between input data and calculated flows exemplifies the data reconciliation of the STAN software (Cencic and Rechberger, 2008, TU Vienna, 2013).

Table S2 Input data for the balance 2010

Main System Al Balance (Fig. 1)

No.	Description	Input data	Input Uncertainty	Calculated flow	Calculated uncertainty	Source
1	Imported scrap	268,500 t/a	8,040 t/a	268,806t/a	7,506 t/a	(Statistik Austria, 2010)
2	Exported scrap	121,000 t/a	3,610 t/a	120,938 t/a	3,563 t/a	(Statistik Austria, 2010)
3	Total scrap input secondary production			248,824 t/a	11,388 t/a	Mass balanced
4	Unwrought Al to secondary production and trade	246,000 t/a	20,575 t/a	264,435 t/a	6,357 t/a	External calculation*
5	Unwrought Al imports	414,000 t/a	12,420 t/a	421,628 t/a	10,278 t/a	Statistik Austria
6	Unwrought Al exports	153,000 t/a	4,550 t/a	152,902 t/a	4,455 t/a	Statistik Austria
7	Billets to extrusion and billet trade	149,000 t/a	17,880 t/a	135,432 t/a	11,904 t/a	External calculation*
8	Rolling ingot	30,000 t/a	12,990 t/a	21,761 t/a	10,859 t/a	(AMAG 2012)
9	Rolling ingot			174,901 t/a	4,816 t/a	Mass balanced
10	Extrusion ingot	92,300 t/a	15,691 t/a	92,861 t/a	11,827 t/a	Confidential data
11	Al for casting application	116,000 t/a	3,480 t/a	115,950 t/a	3,443 t/a	Confidential data
12	Al for other uses	35,000 t/a	1,050 t/a	34,995 t/a	1,049 t/a	Confidential data
13	Al losses via salt slag	2,400 t/a	560 t/a	2,699 t/a	560 t/a	Salt slag shipments (BMLFUW, 2011), 7% Al concentration (Tsakiridis, 2012)
14	Production plates and sheets			133,273 t/a	15,054 t/a	Mass balanced
15	Production foils	17,800 t/a	3,560 t/a	17,800 t/a	3,560 t/a	Confidential data
16	Production extrusions and billet trade	19,4500 t/a	25,285 t/a	190,417 t/a	14,404 t/a	External calculation*
17	Castings to national consumption			39,354 t/a	4,134 t/a	Mass balanced
18	Internal scrap casting	34,000 t/a	1,915 t/a	34,000 t/a	1,915 t/a	30% material efficiency casting (Cullen, 2013), 100 % internal recycling (Svehla et al. , 2012)
19	Internal scrap extrusion	15,500 t/a	4,185 t/a	15,460 t/a	4,120 t/a	Own calculation (confidential)
20	Internal scrap rolling	45,000 t/a	11,970 t/a	45,588 t/a	10,382 t/a	Own calculation (confidential)
21	Exported castings	76,600 t/a	2,298 t/a	76,597 t/a	2,294 t/a	Confidential data
22	Exported desox Al and powder	10,900 t/a	327 t/a	10,900 t/a	327 t/a	(Statistik Austria, 2010)
23	Imported plates, sheets, foils	157,000 t/a	10,000 t/a	157,062 t/a	9,638 t/a	(Statistik Austria, 2010)
24	Imported extrusions	89,200 t/a	3,000 t/a	89,206 t/a	2,990 t/a	(Statistik Austria, 2010)

Table S2 continued

25	Imported Al castings	6,600 t/a	396 t/a	6,600 t/a	396 t/a	(Statistik Austria, 2010)
26	Imported Al products	32,600 t/a	978 t/a	32,601 t/a	978 t/a	(Statistik Austria, 2010)
27	Exported plates, sheets, foils	220,000 t/a	6,600 t/a	219,973 t/a	6,497 t/a	(Statistik Austria, 2010)
28	Exported extrusions	187,000 t/a	5,610 t/a	186,980 t/a	5,547 t/a	(Statistik Austria, 2010)
29	Exported Al products	49,300 t/a	1,479 t/a	49,299 t/a	1,478 t/a	(Statistik Austria, 2010)
30	Manufactured Al for transport use	55,710 t/a	20,802 t/a	55,441 t/a	17,306 t/a	Allocation of semis to end-uses using (EAA, 2005)
31	Manufactured Al for building& infrstructure use	57,646 t/a	21,905 t/a	57,348. t/a	17,777 t/a	Allocation of semis to end-uses using (EAA, 2005)
32	Manufactured Al for mech. eng. use	21,844 t/a	8,247 t/a	21,802 t/a	8,045 t/a	Allocation of semis to end-uses using (EAA, 2005)
33	Manufactured Al for el. eng. use	3,587 t/a	1,363 t/a	3,586 t/a	1,362 t/a	Allocation of semis to end-uses using (EAA, 2005)
34	Manufactured Al for consumer use	9,646 t/a	3,665 t/a	9,638 t/a	3,648 t/a	Allocation of semis to end-uses using (EAA, 2005)
35	Manufactured Al for packaging	33,200 t/a	12,616 t/a	32,996 t/a	1,376 t/a	Allocation of semis to end-uses using (EAA, 2005)
36	In-use transport			66,177 t/a	19,054 t/a	Mass balanced
37	In-use B&I			71,826 t/a	17,861 t/a	Mass balanced
38	In-use mech. eng.			7,695 t/a	8,524 t/a	Mass balanced
39	In-use el. eng.			8,318 t/a	3,684 t/a	Mass balanced
40	In-use consumer			15,336 t/a	5,013 t/a	Mass balanced
41	In-use packaging			32,996 t/a	1,376 t/a	Mass balanced
42	Exported packaging material	17,000 t/a	2,720 t/a	16,615 t/a	1,296 t/a	Private communication (ARA, 2013)
43	Exported (EOL) vehicle	32,500 t/a	8,125 t/a	32,500 t/a	8,125 t/a	Own calculation (Statistik Austria, 2011b, Statistik Austria, 2010c)
44	Old scrap generation transport	6,000 t/a	3,048 t/a	6,000 t/a	3,048 t/a	Own estimation (Less than 30% EOL vehicles nationally processed)
45	Old scrap generation building&infrastructure			21,356 t/a	11,959 t/a	Mass balanced
46	Old scrap generation mech. eng.	4,446 t/a	2,756 t/a	4,446 t/a	2,756 t/a	7% of total old waste generated (Hatayama et al., 2009)
47	Old scrap generation el. eng.	6,351 t/a	3,937 t/a	6,351 t/a	3937 t/a	10% of total old waste generated (Hatayama et al., 2009)
48	Old scrap generation consumer	6,351 t/a	3,937 t/a	6,351 t/a	3,937 t/a	10% of total old waste generated (Hatayama et al., 2009)
49	Old scrap generation packaging	16,400 t/a	483 t/a	16,380 t/a	470 t/a	Old scrap output equals input
50	Total old scrap available for remelting	49,000 t/a	7,840 t/a	49,291 t/a	7,346 t/a	External calculation
51	Manufacturing new scrap	29,200 t/a	3,504 t/a	29,250 t/a	3,467 t/a	Material efficiency manufacturing: 88% Rolling, Packaging 80% (Liu and Müller, 2013)

						88% Extrusion (Cullen et al. , 2013, Hajeeh, 2013)
						97% Casting (Cullen et al. , 2013)
52	New scrap from extrusion processes	22,500 t/a	6,075 t/a	22,416 t/a	5,875 t/a	Own calculation (confidential)

Table S2 continued

Subsystem Waste Management (Fig. 4)

53	Old scrap generation transport	6,000 t/a	3000 t/a	6,000 t/a	3,000 t/a	Own estimation (Less than 30% EOL vehicles nationally processed)
54	Old scrap generation building&infrastructure			21,356 t/a	6,902 t/a	Mass balanced
55	Old scrap generation mech. eng.			4,173 t/a	560 t/a	7% of total old waste generated (Hatayama et al., 2009)
56	Old scrap generation el. eng.			5,961 t/a	800 t/a	10% of total old waste generated (Hatayama et al., 2009)
57	Old scrap generation consumer			5,961 t/a	800 t/a	10% of total old waste generated (Hatayama et al., 2009)
58	Old scrap generation packaging			16,159 t/a	2,031 t/a	Old scrap output equals input (no stock)
59	Packaging Al waste to incineration	6,733 t/a	1818 t/a	6,733 t/a	1,818 t/a	Total solid waste amount incinerated (BMLFUW, 2011); 33.3% commercial waste (0.4% Al content) and 66.6% MSW (0.6% Al content); 80% Al packaging waste and 20% Other Al waste (Taverna et al. , 2010)
60	Other Al waste to incineration	1,722 t/a	464 t/a	1,722 t/a	465 t/a	
61	Packaging Al waste to MBT	3,290 t/a	888 t/a	3,341 t/a	888 t/a	Total solid waste amount to MBT processing (BMLFUW, 2011); 45% Al recovered in MTB processing (Skutan et al., 2006)
62	Other Al waste to MBT	841 t/a	227. t/a	844 t/a	227 t/a	
63	Al shredder input	9,200 t/a	1196 t/a	9,404 t/a	1,193 t/a	Private communication (ARGE S, 2012)
64	Traded Al scrap			30,916 t/a	7,684 t/a	Mass balanced
65	Old scrap packaging (separate collection)	4,436 t/a	133 t/a	4,439 t/a	134 t/a	Private communication (ARA, 2013)
66	Al from disassembled consumer goods	2,200 t/a	279 t/a	2,211 t/a	279 t/a	(EAK, 2010)
67	Oxidation losses			5,518 t/a	1,563 t/a	Mass balanced, considering 30% Al transferred to bottom ash
68	Metall Al residues in bottom ash			2,536 t/a	1,016 t/a	30% Al in bottom ash (Grosso et al., 2011)
69	Metall Al residues in MBT			2,302 t/a	504 t/a	Mass balanced; considering 45% recovery rate

70	Process residues shredding			19 t/a	5 t/a	Private communication (ARGE S, 2012)
71	Recovered Al from incinerators	400 t/a	52 t/a	400 t/a	51 t/a	Private communication (MA 48, 2013)
72	Recovered Al from MBT			1,883 t/a	412 t/a	45% Al recovered in MTB processing (Skutan et al., 2006)
73	Shredder output			9,384 t/a	1,193 t/a	Mass balanced

* Mass balancing of detailed subsystems in STAN

Trade of final goods

Al flows originating from the trade of final goods are calculated by selecting relevant SITC codes from foreign trade statistics (Statistik Austria, 2010). Data on average Al contents for the different product codes are derived from various data sources, mainly from KEMI database (SCA, 2010). Missing and unobtainable data has been complemented by assumptions that are based on different research studies (Truttmann and Rechberger, 2006) (Ducker, 2011) (Troyes, 2009) (Liu and Müller, 2013, Recalde et al. , 2008, Salhofer and Tesar, 2011). Concerning the reported hierarchy level data is analysed on the group level of SITC rev.4 statistics. A determination of Al flows on a subgroup level of SITC classification is virtually impossible in view of hardly existing data on Al concentration in final goods. Data used for the calculations of Al flows from the foreign trade of Al containing goods is given in Table S2.

Table S3 Calculated Al flows from foreign trade of Al containing products for selected SITC codes

SITC rev.4	Import [t]	Export [t]	Source	Al content [weight%]	Uncertainty Al content	Source	Al imported [t]	Al exported [t]
Transport								
712	2,838	7,632	Statistik Austria	1	0.4%	KEMI	28	76
713	186,745	281,959	Statistik Austria	25	14.2%	BMW	46,686	70,490
714	506	3,078	Statistik Austria	25	14.2%	estimate based on 713	126	770
716	50,789	70,193	Statistik Austria	2	0.7%	KEMI	1,016	1,404
718	16,157	11,583	Statistik Austria	2	1.1%	estimate based on 716	323	232
781	521,127	232,343	Statistik Austria	10	1.3%	Ducker	52,113	23,234
782	96,401	167,275	Statistik Austria	6	2.1%	Liu et al,	5,784	10,037
783	38,978	41,928	Statistik Austria	15	5.3%	KEMI	5,847	6,289
784	412,989	381,437	Statistik Austria	10	5.6%	estimate based on 713	41,299	38,144
785	22,939	13,596	Statistik Austria	16	5.7%	KEMI	3,670	2,175
786	89,693	71,047	Statistik Austria	15	1.9%	EAA	13,454	10,657
791	149	555	Statistik Austria	1	0.4%	KEMI	1	6
792	2,615	840	Statistik Austria	13	4.6%	KEMI	340	109
793	80	3	Statistik Austria	2	0.7%	KEMI	2	0
	1,442,005	**1,283,468**					**170,690**	**163,622**
Building and Infrastructure								
69121	5,370	1,716	Statistik Austria	90	0.1	estimate	4,833	1,544
69129	38,203	25,770	Statistik Austria	90	0.1	estimate	34,383	23,193
	43,573	**27,486**					**39,216**	**24,737**
Machinery/Equipment								
721	70,829	68,681	Statistik Austria	1	0.4%	Graedel, KEMI	708	687

Table S3 continued

722	27,481	53,265	Statistik Austria	0.5	0.2%	KEMI	137	266
723	125,403	140,445	Statistik Austria	0.5	0.2%	Graedel	627	702
724	7,115	8,653	Statistik Austria	1	0.4%	Graedl, KEMI	71	87
725	10,378	25,179	Statistik Austria	2	0.7%	KEMI	208	504
726	10,454	13,977	Statistik Austria	2	0.7%	KEMI	209	280
727	7,561	8,452	Statistik Austria	1	0.4%	KEMI	76	85
728	114,796	172,926	Statistik Austria	2	0.7%	KEMI	2,296	3,459
731	11,850	14,113	Statistik Austria	1	0.6%	estimate based on 725, 726, 727	118	141
733	5,646	17,718	Statistik Austria	1	0.4%	Graedel	56	177
735	13,156	8,970	Statistik Austria	1	0.4%	Graedel	132	90
737	21,591	33,962	Statistik Austria	0.5	0.2%	KEMI	108	170
741	82,714	106,793	Statistik Austria	2	0.7%	estimate	1,654	2,136
742	30,078	18,382	Statistik Austria	2	0.7%	KEMI	602	368
743	79,492	103,865	Statistik Austria	6	2.1%	KEMI	4,770	6,232
744	116,975	140,575	Statistik Austria	1	0.4%	KEMI	1,170	1,406
745	51,585	26,933	Statistik Austria	1	0.6%	estimate based on 725, 726, 727, 737	516	269
748	85,955	41,349	Statistik Austria	2	1.1%	estimate	1,719	827
749	13,628	27,588	Statistik Austria	2	1.1%	estimate	273	552
69212	446	204	Statistik Austria	90	7.2%	estimate	402	183
69242	9,310	19,449	Statistik Austria	90	7.2%	estimate	8,379	17,504
69244	181	7	Statistik Austria	90	7.2%	estimate	163	6
69313	279	3,336	Statistik Austria	90	7.2%	estimate	251	3,002
69440	1,100	888	Statistik Austria	90	7.2%	estimate	990	799
	898,002	**1,055,710**					**25,634**	**39,930**

Table S3 continued

Consumer Products								
761	29,204	14,373	Statistik Austria	2	0.5%	Trut&Rechberger	584	287
762	3,396	655	Statistik Austria	6	1.6%	Trut&Rechberger	204	39
763	2,963	967	Statistik Austria	2	0.5%	Trut&Rechberger	59	19
764	18,412	7,583	Statistik Austria	2	0.5%	Trut&Rechberger	368	152
775	116,860	51,559	Statistik Austria	2	0.5%	Trut&Rechberger, Salhofer, KEMI	2,337	1,031
69743	4,325	1,575	Statistik Austria	90	7.2%	estimate	3,892	1,417
69753	1,224	1,573	Statistik Austria	90	7.2%	estimate	1,102	1,415
751	18,698	5,652	Statistik Austria	5	1.3%	Trut&Rechberger, Salhofer, KEMI	935	283
752	15,567	4,912	Statistik Austria	5	1.3%	Trut&Rechberger, Salhofer, KEMI	778	246
759	8,246	4,546	Statistik Austria	5	1.3%	Trut&Rechberger, Salhofer, KEMI	412	227
	218,895	93,394					**10,672**	**5,117**
Electrical Engineering								
771	40,300	82,201	Statistik Austria	16	5.7%	KEMI	6,448	13,152
772	70,568	74,529	Statistik Austria	10	5.6%	estimate based on 771	7,057	7,453
773								
77316	91,855	56,602	Statistik Austria	25	14.0%		22,964	14,151
77317	10,429	3,527	Statistik Austria	50	28.0%	est	5,215	1,763
774	2,187	2,604	Statistik Austria	2	1.1%	estimate based on 763, 752	44	52
776	14,125	18,374	Statistik Austria	2	1.1%	estimate based on 763, 753	282	367
778	114,404	137,274	Statistik Austria	2	1.1%	estimate based on 763, 754	2,288	2,745

Table S3 continued

343,868	375,110			**44,298**	**39,684**
5,892,688	5,670,338		**Total Al**	**290,509**	**273,091**

Bottom-up evaluation of existing “In-Use” stock

In transportation all quantity data is taken from (Statistik Austria, 2011b, 2014). For buildings&infrastructure data on Al content for private and commercial buildings is taken from (Recalde, Wang, 2008). A detailed investigation of in-use stocks by means of dynamic systems analysis is not within the scope of this study, which highlights the focus of the analysis on resource flows and which is why the Al stock estimates should be treated as screening level results. Especially for the field of consumer goods inventory statistics are hardly to obtain, which potentially leads to higher uncertainties on these numbers. For electrical equipment the Al amount in national power grid is calculated, having in mind that Al use in electrical application is not limited this. For machinery equipment no data on national inventory is available, hence no calculation of in-use stock is possible by bottom-up approach. A compilation of the bottom-up data is given in Table S3.

Table S4: Data on bottom-up calculation of the existing in-use stock

Transport				
	quantity [number]	Al content [kg]	Source	Total Al [kg]
road vehicles				
cars	4.441.027	calculated for existing car fleet and Al content for each cohort	(Ducker, 2011, IPTS, 2008)	468.135.451
bikes	727.852	30	(Recalde, Wang, 2008, SCA, 2010)	21.835.560
busses	9.648	800	(Recalde, Wang, 2008)	7.718.400
trucks	379.965	250	(SCA, 2010)	94.991.250
tractors, machines	533.389	40	(SCA, 2010)	21.335.560
trailers	568.453	150	own estimation	85.267.950
semitrailers	44.665	1.000	(Troyes, 2009)	44.665.000
agricultural used trailers	47	100	own estimation	4.700
house trailer	36.221	150	own estimation	5.433.150
trailers for working machines	9.595	50	own estimation	479.750
special trailers	2.779	50	own estimation	138.950
rail vehicles				
electric locomotive	889	**1.640**	own estimation	1.457.960
diesel locomotive	520	**328**	own estimation	170.560
railcars	645	**12.600**	own estimation	8.127.000
passenger wagon	2.524	**600**	own estimation	1.514.400
aircrafts				
< 5.700kg	817	**910**	(Liu and Müller, 2013)	743.470
5.700-20.000kg	132	**9.800**	(Liu and Müller, 2013)	1.293.600
> 14.000	185	**28.000**	(Liu and Müller, 2013)	5.180.000
other aircrafts	207	**750**	(Liu and Müller, 2013)	155.250
				768.647.961

Table S4 continued

Building&Infrastructure				
	quantity [m²]	[kg/m²]	Source	Total Al [kg]
private housing	323.606.880	1	(Statistik Austria, 2011a)	323.606.880
offices	17.500.000	4	(Energie Markt Analyse, 2012)	70.000.000
shops, stores	15.700.000	4	(Energie Markt Analyse, 2012)	62.800.000
hospitals	7.700.000	4	(Energie Markt Analyse, 2012)	30.800.000
hotels	38.000.000	4	own estimations	152.000.000
restaurants	5.000.000	4	own estimations	20.000.000
public buldings	12.000.000	4	own estimations	48.000.000
industry and business	75.000.000	4	own estimations	300.000.000
infrastructure buildings		8,6 [kg/cap.]	(Recalde, Wang, 2008)	72.240.000
				1.079.446.880
El. Infrastructure				
	network length [km]	[kg/km]		
480/900V	165.989	1,19	(E-Control, 2011, Energie AG, 2013)	197.527
6/10/20/30/60 kV	67.833	0,94	E-Control 2011, Energie AG 2013)	63.763
110 kV	11.135	3,16	E-Control 2011, Energie AG 2013)	35.187
220-380kV	6.390	7,61	E-Control 2011, Energie AG 2013)	48.627
equipment (e.g. transformators etc.)				1.700
				346.804.290
Consumer				
	quantity [number]	Al content [kg]	Source	Total Al [kg]
private inventory				
mobile phones	3.280.641	0,0057	(Salhofer and Tesar, 2011)	18.700

Table S4 continued

PC	2.559.621	0,11	(Salhofer and Tesar, 2011)	281.558
				0
electric cooker	3.244.590	1,8	(Recalde, Wang, 2008)	5.840.262
gas stove	396.561	1,6	Recalde, Wang et al. 2008)	634.498
refrigerator	3.569.049	2,1	Recalde, Wang et al. 2008)	7.495.003
dishwasher	2.667.774	1,4	Recalde, Wang et al. 2008)	3.734.884
washing machine	3.496.947	1,9	Recalde, Wang et al. 2008)	6.644.199
tumble dryer	1.225.734	1,9	Recalde, Wang et al. 2008)	2.328.895
TV sets	3.496.947	0,35	Recalde, Wang et al. 2008)	1.223.931
video	2.775.927	0,063	(Salhofer and Tesar, 2011)	174.883
cameras	865.224	0,031	(Salhofer and Tesar, 2011)	26.822
Hifi	2.307.264	0,126	(Salhofer and Tesar, 2011)	290.715
				28.694.350
commercial inventory				
mobile phones	2.623.436	0,0057	(Salhofer and Tesar, 2011)	14.954
PC	2.843.403	0,11	(Salhofer and Tesar, 2011)	312.774
electric cooker	176.500	1,8	(Recalde, Wang, 2008)	317.700
gas stove	176.500	1,6	Recalde, Wang et al. 2008)	282.400
refrigerator	1.204.000	2,1	Recalde, Wang et al. 2008)	2.528.400
dishwasher	352.000	1,4	Recalde, Wang et al. 2008)	492.800
washing machine	112.262	1,9	Recalde, Wang et al. 2008)	213.298

Table S4 continued

tumble dryer	112.262	1,9	Recalde, Wang et al. 2008)	213.298
TV sets	873.149	0,35	Recalde, Wang et al. 2008)	305.602
				4.681.226
				33.375.576
			Total	**2.256.969.057**

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Paper 2

Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria

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Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria

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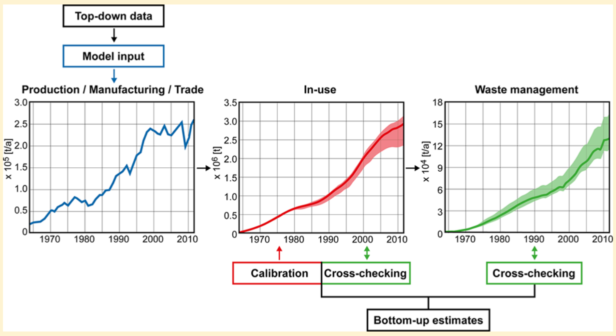
Supporting Information

ABSTRACT: A calibrated and validated dynamic material flow model of Austrian aluminum (Al) stocks and flows between 1964 and 2012 was developed. Calibration and extensive plausibility testing was performed to illustrate how the quality of dynamic material flow analysis can be improved on the basis of the consideration of independent bottom-up estimates. According to the model, total Austrian in-use Al stocks reached a level of 360 kg/capita in 2012, with buildings (45%) and transport applications (32%) being the major in-use stocks. Old scrap generation (including export of end-of-life vehicles) amounted to 12.5 kg/capita in 2012, still being on the increase, while Al final demand has remained rather constant at around 25 kg/capita in the past few years. The application of global sensitivity analysis showed that only small parts of the total variance of old scrap generation could be explained by the variation of single parameters, emphasizing the need for comprehensive sensitivity analysis tools accounting for interaction between parameters and time-delay effects in dynamic material flow models. Overall, it was possible to generate a detailed understanding of the evolution of Al stocks and flows in Austria, including plausibility evaluations of the results. Such models constitute a reliable basis for evaluating future recycling potentials, in particular with respect to application-specific qualities of current and future national Al scrap generation and utilization.



1. INTRODUCTION

Increasing efforts to recycle metals, especially for tackling environmental and economic issues with a view to furthering the efficient and sustainable management of resources, has resulted in a large interest in the investigation of anthropogenic stocks and flows in society.[1−3] Existing in-use Al stocks are a viable source for future secondary Al production. For this reason, the understanding of these stocks and the associated flows is crucial for optimizing future Al resource management.

Material flow analysis (MFA) of anthropogenic Al has been conducted to various extents. Static models of the Al flows are available on global[4] and national[5] scales. Even though static models typically provide insight into existing MFA systems at a high level of detail, lately, patterns of metals use and management have been investigated to a large extent using dynamic models to capture time-dependent aspects such as the development of the in-use stock and the associated postconsumer scrap flows. Dynamic studies on a country level are available for the U.S.,[6−8] U.K.,[9] Italy,[10] Spain,[11] Japan,[12] and China.[12,13] Global dynamic models analyzing a plurality of countries in order to derive information on global stocks and flows have also been developed.[14,15] Moreover, an extensive review[16] on existing dynamic MFAs of metals has been conducted. Even though such studies on metals, especially iron and Al, already exist for various countries on different scales, it is typically not possible to calibrate these models or to check model plausibility based on independent data. In addition to the lack of data-based model evaluation, the uncertainty of the modeling results and their sensitivity with respect to model parameters are often ignored or not dealt with in great depth. Furthermore, the reliability of estimates of potential secondary resource flows (postconsumer stage) cannot be evaluated in global models because the corresponding data can only be gathered on a national level with consistent reporting and data collection schemes. Another option for model calibration and validation is the combination of dynamic top-down models (i.e., production and trade data are used to split flows into various applications and sectors) and static bottom-up models to quantify (parts of) the same system, which has, however, not been done so far.[16] Existing studies[15,17] primarily focus on calibration measures in order to close the mass balance through mathematical adjustment of model parameters (sector split ratios, scrap collection rates, etc.). Although methods for data

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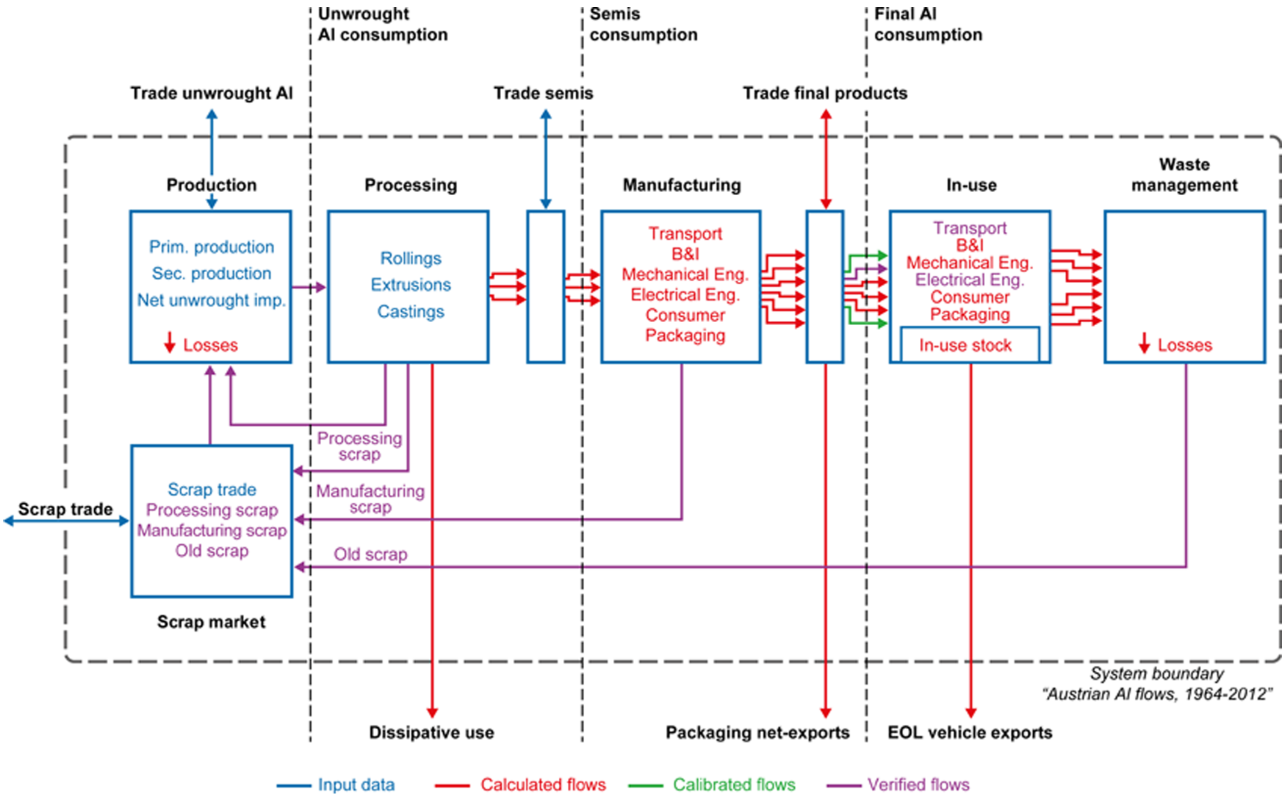

Figure 1. System definition of the national Al flow system. The different bases for determining flows and stocks (input-data based, model outcome, calibrated flow (parameter adjustment), and cross checked-model outcome (verified flow)) of the model are indicated by the various colors.

rectification and reconciliation of mass and energy flow data exist and are widely applied to industrial processes[18−20] and also to static MFA,[21] efforts to cross check and validate dynamic material flow models with independent estimates are largely missing.

In the present study, a novel procedure for contrasting top-down model results with bottom-up estimates (based on independent data sources) for selected Al stocks and flows is applied to develop a calibrated dynamic model of Austrian Al flows from 1964 to 2012 for determining in-use stocks and scrap flows. Besides analyzing the Austrian Al budget from a resource management perspective (old scrap generation, quantification of in-use stock) three major questions are addressed: (1) How can a dynamic model be calibrated by combining dynamic modeling with static MFA and additional bottom-up estimates? (2) To which extent can parameter uncertainties and their effects on the model results be determined for such a dynamic MFA? (3) What additional information can be derived from a dynamic MFA on the national level in comparison to more aggregate (global) models?

2. MATERIALS AND METHODS

2.1. Model Structure and Input Data. Figure 1 shows the basic flows and processes of the modeled system. System boundaries correspond to the geographical border of Austria and comprise the time series from 1964 to 2012 with 48 one year increments. The initial stock of Al is assumed to be zero, and the principle of mass conservation is applied for balancing Al flows for all time-steps considered in the model.[21] The stocks and flows of Al are determined using a top-down modeling approach driven by historic Al production data. Detailed information on input quantities, model parameters, and data sources are provided in the Supporting Information. Primary and secondary Al production, including foreign trade of unwrought metal and scrap utilization (processing/manufacturing/old scrap and foreign scrap trade), are summarized in the production process. Since the last Austrian bauxite production site closed in 1965, bauxite mining is not included in the model.[22]

The starting point for the model is given by a data series on semifinished goods (rollings, extrusions, castings) produced in Austria. Material efficiency parameters are used to determine amounts of processing scrap and manufacturing scrap with respect to application. Foreign trade flows of semis are considered on the basis of the UN Trade Classification (SITC). For the allocation of Al to the six in-use sectors (Transport, Building and Infrastructure, Mechanical Engineering, Electrical Engineering, Consumer and Packaging), transfer coefficients (tc_{sec}) for sector splits, varying over time, are computed. Indirect flows of Al originating from the foreign trade of Al-containing products are considered on the basis of specific SITC codes and their average Al contents (see the Supporting Information). Al discards at the in-use stage are calculated for each sector using specific Weibull lifetime functions. Due to the lack of data, the lifetime functions are considered to be constant over time, except for the transport sector, for which time-dependent average lifetimes ($\tau(t)$) are used.[23,24] A general formulation of stock and output calculation is given in formulas 1 and 2, with the year of modeling t as variable, $\tau(t)$ the average lifetime, and k the shape parameter of the Weibull function $p(t)$ applied. Exports of filled packaging

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material are considered separately using a fixed transfer coefficient derived from bottom-up data. For the export of end-of-life (EOL) vehicles, a time-dependent transfer coefficient is used, in order to consider increasing foreign trade activities in the past decades. Collection and processing losses at the end of life stage are considered separately for transport and packaging Al waste, where national bottom-up estimates are available (Supporting Information). Losses in other sectors are based on literature data.[11,25]

$$S(t) = S(0) + \sum_{t=1964}^{2012} \text{input}(t) - \text{output}(t) \tag{1}$$

$$\text{output}(t) = \sum_{t'<t} \text{input}(t') \times p(t - t', \tau(t), k) \tag{2}$$

2.2. Model Calibration and Plausibility Checks. Similar to previous dynamic MFA studies, top-down model calculations (i.e., flows are determined on the basis of production and trade data and subsequently split into the various applications and sectors based on literature data) are used to determine flows and stocks of Al. In order to increase reliability of the model results, calibration of model parameters as well as intensive plausibility checks for selected stocks and flows have been performed. Bottom-up estimates refer to data which are available for a certain year from data sources which are independent from national production and trade statistics, e.g., the number of registered cars in a specific year. While classical dynamic MFA is limited to consistency checks of modeled stocks and flows under given mass balance constraints, in this study, a novel approach for model calibration and cross-checking based on independent estimates is presented.

Calibration has been conducted for the in-use inputs into the transport and the packaging sector. For transport inputs, a bottom-up calculation of the Al amount in the national vehicle fleet (passenger and commercial vehicles) is set up for the time period of 1990–2012 using official inventory data[26] and studies[27,28] on time-dependent Al contents in vehicles. The transfer coefficient of Al directed from manufacturing to the transport sector is adjusted according to bottom-up estimates between 1990 and 2012 by linear optimization. Inputs in the packaging sector have been calibrated with bottom-up data on Al consumed for packaging applications between 1998 and 2010 provided by the Austrian packaging recycling association.[29] The data set includes the amount of nationally produced Al for packaging as well as net-imports of unused and filled Al packaging. Transfer coefficients of Al flows from manufacturing to the remaining sectors (Building and Infrastructure, Mechanical Eng., Electrical Eng., and Consumer), for which no bottom-up estimates for calibration are available, are adjusted proportionally in order to ensure that all the tc_{sec} sum up to unity. Detailed information on the specification of tc_{sec} is available in the Supporting Information.

Plausibility checks with bottom-up estimates have been performed for selected stocks and flows across the entire model. Within the production process, total domestic scrap generation (processing, manufacturing, and old scrap) and the net scrap imports are compared with a separately compiled data set[30−32] on secondary aluminum production. Additionally, the total unwrought Al consumption (primary production, secondary production, and net unwrought metal imports) is calculated and cross-checked in an upstream (production) and a downstream (semiprocessing) direction (cf. Supporting Information). At the in-use stage, the stock of Al in transport applications as well as the Al stock in electrical engineering applications is checked against bottom-up calculations. Therefore, the length of the power grid network and Al content per km[33−35] have been considered for all levels of voltage to estimate current in-use stock. For the in-use transportation stock, a bottom-up data set with Al stored in all types of vehicles is generated for the time period between 1990 and 2012, using official bottom-up inventory data and vehicle specific time-dependent Al contents. Finally, the total old scrap generation (iv) as well as the discrimination between processing, manufacturing and old scrap simulated by the dynamic model is contrasted with the results of a previous (static) MFA study[5] on Austrian Al flows conducted in 2010.

2.3. Uncertainty and Sensitivity Analysis. On the basis of uncertainty analysis concepts used in life cycle assessment,[36] parameter uncertainty is distinguished from model uncertainty. The former is caused by incomplete knowledge about the real value of certain parameters, whereas the latter originates from an imperfect or neglected consideration of real world effects in the model.

Parameter uncertainty is analyzed for three groups of parameters, namely, Al concentration in final goods, tc_{sec}, and average lifetimes, leading to a total of 12 parameters considered in the uncertainty analysis. Using Monte Carlo Simulation (MCS), 1000 individual values are generated for each uncertain parameter and used to feed the dynamic MFA model and to determine respective results. Normal distributions given by mean values and standard deviations are assumed for Al concentration in final goods and for tc_{sec}. In-use lifetimes are described by Weibull functions. Data from the literature are used for mean values[14,37,38] and the uncertainty ranges[6,37] of the parameters. Detailed information on parameter values and coefficients of variance is provided in the Supporting Information.

By performing global sensitivity analysis, the relationship between the uncertainty of the resulting outputs (e.g., total old scrap generation) and the uncertainty of the inputs is analyzed (sensitivity analysis addressing parameter uncertainty). Variance-based techniques decompose the total uncertainty of a model output into contributions from each uncertain input parameter as well as contributions from the interaction of parameters. Total uncertainty is, finally, split up into contributions from the uncertainty of single parameters (first order effects), uncertainty originating from the combination of two parameters (second order effects), etc.[39] The relation between the conditional variance ${\sigma_{E(Y|X_i)}}^2$ (holding the selected parameter at its "true" value) for each parameter i and the unconditional variance (all parameters uncertain) ${\sigma_Y}^2$ (eq 3) is called the first order index, providing information on the effect of varying a single input parameter i on the result Y (=first order effect).[39,40]

$$S_i = \frac{{\sigma_{E(Y|X_i)}}^2}{{\sigma_Y}^2} \tag{3}$$

For additive models, first order indices sum up to unity (eq 4), thus providing a direct measure for the effect of X_i on Y. For nonadditive models, the interaction effects of input parameters have to be considered in order to explain the full unconditional variation of the model output[40] (=uncertainty of the model results).

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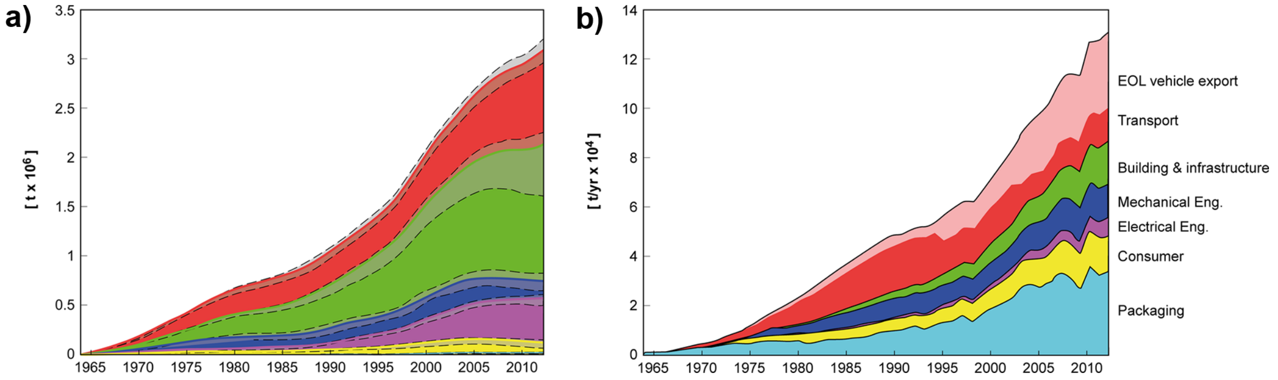

Figure 2. Austrian Al in-use stocks and old scrap flows. Uncertainties are calculated with respect to the sector split, average lifetimes, and Al concentration in final goods. Ranges of uncertainty are indicated as shaded gray areas and correspond to a 95% confidence interval.

$$\sum_{i=1}^{n} S_i = 1 \tag{4}$$

First order effects of parameter variations are determined for the total old scrap Al flow in this model using the EASI algorithm.[41] EASI performs variance-based global sensitivity analysis based on a Fourier-based technique executed in a MATLAB postprocessing module (cf. Section 10 of the Supporting Information).

Model uncertainties arise from the definition of the MFA model itself (model uncertainty) and are analyzed with respect to the lifetime model definition and the assumption of the amount of Al stock at the beginning of the modeling period. A clear lifetime model definition is required to clarify whether the share of products not leaving the in-use phase, either due to hibernation or obsolescence, are included in the chosen lifetime functions or not. The effect of Al in obsolete products in the stock or in products in hibernation instead of scrapping is therefore simulated by an estimated set of parameters (accounting for a specific share of end-of-life (EOL) products not leaving the stock) and further discussed in the Supporting Information, in order to illustrate the effect of model uncertainty. Furthermore, assumptions on initial in-use stocks are considered as a model uncertainty. The initial in-use stocks in 1964 have most likely not been equal to zero, which is however assumed in the model. Therefore, the effects of assuming an initial stock of 40 kg/cap. on old scrap generation and in-use stock development are investigated as part of the uncertainty analysis (see Figure S6c,d of the Supporting Information).

3. RESULTS

3.1. Model Calibration. The tc_{sec} of the transport sector has been calibrated using bottom-up data (of new vehicles being annually registered) to accomplish an excellent fit between modeled input and bottom-up estimates for the last 20 years (Figure S3 top, Supporting Information). For the packaging sector too, bottom-up data for the last 10 years and modeled input are brought into good accordance (Figure S3, bottom, Supporting Information). For the remaining sectors, calibration of tc_{sec} is not possible due to missing bottom-up estimates. However, intensive testing of outputs is carried out across all stages of the model (cf. Section 3.3) in order to check its consistency and reliability.

3.2. National Aluminum Stocks and Flows. Figure 2 shows the development of the in-use stock as well as the trends in old scrap generation. The Building and Infrastructure in-use stock exhibits the biggest increase of all sectors during the last 30 years due to high average lifetimes. About 40% of all existing anthropogenic Al is currently stored in buildings, but due to limited knowledge about the actual average lifetime of Al in buildings (e.g., renovation, technical replacement), uncertainties for the building stock are the highest. Transport stock clearly shows an increasing trend over the past 15 years, which is explained by a trend for lightweight construction in modern vehicles typically replacing iron and steel with Al. The Al stock in electrical engineering applications is moderately increasing, while the stocks in mechanical engineering and consumer products (e.g., electrical and electronic appliances) already provide some evidence of saturation. Nevertheless, due to the strong demand for Al in transport applications, total in-use stock is still increasing at a current rate of 2%/year (2010−2012). Uncertainties are indicated as shaded areas in Figure 2a. The left-skewed distribution (indicated by a larger uncertainty interval for values bellow the median, e.g., Building and Infrastructure sector) is caused by the convolution of normally distributed variables (tc_{sec}, Al concentration in final goods) and the Weibull lifetime distribution functions. The longer the average lifetime of products in a sector, the more skewed is the resulting distribution for Al in the in-use stock. Consequently, the probability of substantially overestimating the amount of Al in stock is lower than the other way around. Detailed information about the resulting probability distributions for total stock and total old scrap can be found in Section 9 of the Supporting Information.

Current total old scrap generation is dominated by Al from transport + vehicle exports (34%) and packaging (20%) applications, amounting to 134.000 t/year. Together with Al scrap from buildings, about two-thirds of total Al leaving the in-use stage is generated from these three sectors. Al losses through the export of used vehicles (private and commercial) amount to about 31.000 t or one-third of total national old scrap generation. Considering further losses from illegal exports of WEEE, as well as collection and processing losses, the total amount of aluminum available for remelting (see Figure S4d, Supporting Information) decreases to 100.000 t, which is only 75% of the total amount of Al leaving in-use in 2012.

Looking at the trends of the past 30 years (Table 1), the industrial Al consumption increased by a factor of 4 between 1982 and 2012. In the same period, net imports of Al scrap increased by a factor of 11, clearly indicating the shift of national industry from primary to secondary production. Even

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Table 1. Trends of Selected Flows in the National Material Flow System between 1982 and 2012[a]

	1982	1992	2002	2012
	Industry and Trade			
unwrought Al consumption [t]	139,000	303,000	377.000	566,000
net scrap import [t]	14,000	13,000	57,000	158,000
net import semis [t]	−22,000	−29,000	−50,000	−116,000
net import final products [t]	−2,000	15,000	26,000	18,000
	In-Use			
in-use stock [kg/cap.]	94	150	280	360
final Al consumption [kg/cap.]	6.9	17	25	25
old scrap generation [kg/cap.]	3.5	6.1	8.8	12

[a]Unwrought Al demand includes prim. and sec. Al production + net imports of unwrought Al. Net imports of semis and final products are based on the SITC categories reported in the Supporting Information. Note: Stocks in 1982 and 1992 are influenced by the assumption of zero stocks at the beginning of the model period (cf. Figure S6c,d, Supporting Information).

though national secondary Al production expanded heavily over time, Al scrap exports have apparently not been affected by this trend and are still steadily increasing. Regarding the foreign trade of semifinished products, Austria is clearly an exporting country whereas indirect Al flows from the foreign trade of final products are quite balanced.

Austrian total in-use stocks amount to 360 kg/cap in 2012. Demand at the consumer level increased heavily over time but now indicates some saturation at around 25 kg/(cap year). Old scrap generation has increased by a factor of 4 to 12 kg/cap, which corresponds to about 50% of current domestic Al consumption.

Existing literature shows 160−410 kg/cap for European[10,12,14] total in-use stocks and 300−520 kg/cap[6,14,42] for the U.S., but results can differ since they heavily depend on the model parameters chosen, especially for parameters like tc_{sec}; for average lifetimes, no generally applicable numbers are available. Sector split ratios are country specific and data are lacking, whereas average lifetimes are statistically difficult to determine for some sectors (buildings, engineering applications) because of high lifetimes and missing (historical) data.

3.3. Plausibility Checks and Model Validation. Since comprehensive and continuous bottom-up estimates for the calibration of inputs for all sectors could not be established due

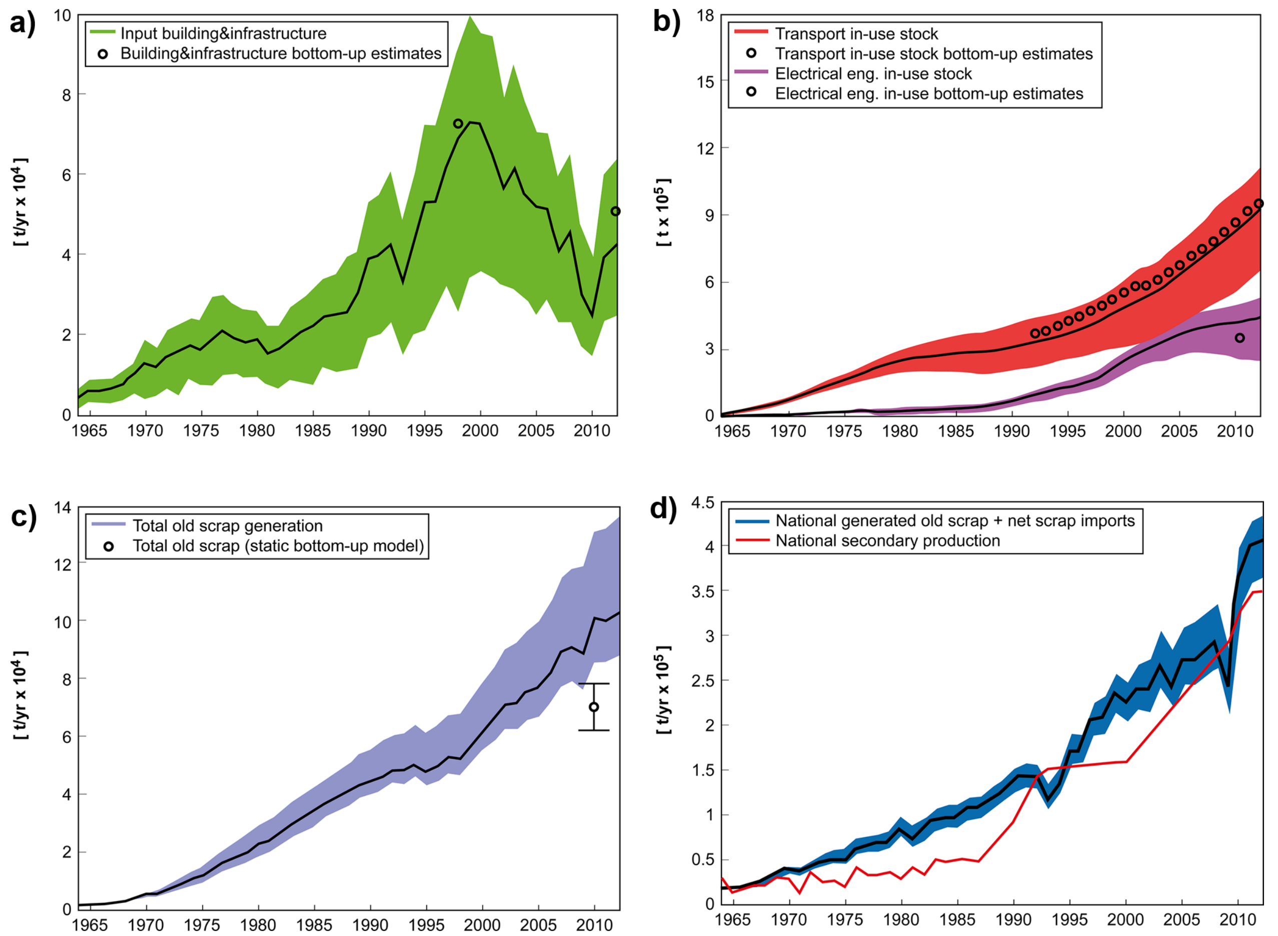

Figure 3. Cross-checks of model results against bottom-up data. (a) Inputs into the building and infrastructure sector, (b) transport and electrical eng. in-use stocks, (c) total old scrap generation (excl. EOL vehicle exports), (d) modeled total scrap generation (new + old scrap) plus net scrap imports vs recycled scrap in national secondary production.

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to data limitations, the inputs and stocks of the remaining sectors are cross-checked with bottom-up estimates referring to specific time points. The calculated inputs into the building and infrastructure sector are cross-checked with data published by the Al industry[43] in 2012, which states that the total amount of Al consumed in buildings in Germany, Austria, and Switzerland increased by a factor of 3.5 during the last 40 years (loops in Figure 3a). Another bottom-up study[44] for the Austrian Al consumption in buildings is available for the year 1998, with the estimate for the Al consumption of the Building and Infrastructure sector being in good agreement with the model results (see Figure 3a).

In Figure 3b, the plausibility checks for the in-use stocks are illustrated. For the transport sector, the model (calibrated tc_{sec}) corresponds very well with bottom-up estimates of the national vehicle fleet. Note that nonroad vehicles are disregarded in the estimate, because they are also not include in the modeled transport stock due to missing calibration data, but the difference between road vehicle stock and total transport stock (including railroad vehicles, airplanes, and ships) is only 2% (2012) and therefore negligible (cf. Section 4 of the Supporting Information). Stocks of electrical engineering applications are compared with bottom-up calculations on the Austrian power grid network. The calculated value of Al stored in the power grid in 2010 is indicated in Figure 3b. Since the electrical engineering sector contains some further applications besides power distribution grids, it is reasonable that the modeled stock is above the bottom-up estimate. For the remaining in-use stocks, it is widely not possible to derive comprehensive bottom-up estimates on a national level for plausibility testing. Furthermore, the total scrap amount modeled (Figure 3c) is compared with the results from a static model[5] on national Al flows in 2010. The amount of old scrap from dynamic modeling is about 30% above the result from the static MFA. The observed deviation may be attributed to one or several of the following factors: (a) The results on total old scrap in the static model originate from balancing the inputs to secondary production processes, which is why the uncertainties about other production inputs (e.g., new scrap, scrap imports, and prim. Al) have a direct influence on the estimated amount of old scrap. (b) Bottom-up studies are limited with respect to the comprehensive accounting of Al in diversified product streams due to incomplete data; thus, they can be regarded as a somewhat lower estimate in comparison with top-down methods. (c) External effects can disrupt continuity in the system (e.g., bonus for scrapping old cars in Austria in 2009) but are not considered in the dynamic model, which could also explain some of the deviation between static and dynamic model results.

Finally, in Figure 3d, the calculated scrap generation (new scrap, old scrap, and net-scrap imports) is cross-checked with secondary production to assess the overall balance and model consistency. Scrap generation estimated by the model is substantially higher for most of the modeling period than the amount of scrap used in secondary production, based on an average primary Al content of 15% and Al losses of 5% in the remelting and refining process. The difference in the two curves may be explained by higher Al losses during waste processing and scrap recycling in the past, as the relative losses in waste management and Al smelters have been assumed constant over time. Thus, it is probable that a part of the scrap generation modeled between 1964 and the early 2000s was not recovered but rather deposited at landfills (cf. Figure 3d).

The importance of calibration for the evaluation of individual in-use sectors is highlighted by the comparison of modeled in-use Al stock of the transport sector against model estimates using literature-based or temporally constant tc_{sec} parameters in Figure 4. The in-use stock of the transport sector, calculated

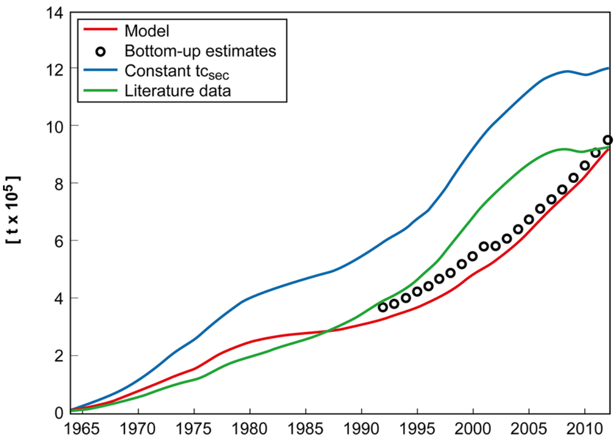

Figure 4. In-use stock development of the transport sector. Result of the calibrated model (red line), bottom-up estimates (black circles), result based on tc_{sec} kept constant at the level of year 2012 (blue line), and result using literature data for tc_{sec} (green line).

from calibrated input flows, is in full agreement with independent bottom-up estimates, whereas modeling results using noncalibrated (Figure S1b of the Supporting Information) or constant parameters (tc_{sec} values for 2012 were kept constant over time) deviate substantially from bottom-up estimates (see Figure 4). From this comparison, it is obvious that the use of specific, calibrated model parameters is essential to capture the current trends of transport in-use stock development and to allow for meaningful extrapolations.

3.4. Sensitivity Analysis. *Sensitivity Analysis Addressing Parameter Uncertainty.* Most dynamic MFA studies use "one-at-a-time" types of analysis[16] for uncertainty and sensitivity analysis, if at all, global sensitivity analysis[39] has not been widely performed in dynamic MFA studies. Hence, a global sensitivity analysis has been carried out for the amount of Al old scrap calculated by the dynamic material flow model with respect to first order effects. Therefore, the simulated parameter inputs for every year together with calculated old scrap values for the same year are passed to the EASI function.

From Figure 5, it is apparent that the total sum of all first order effects is above unity at the beginning of the modeling period, which indicates that input parameters, especially with respect to tc_{sec}, are not independent. At the beginning of the modeling period, the sector split ratio on packaging exhibits a great impact on total old scrap, which seems to be quite intuitive since most packaging Al has a fast turnover and does not contribute to in-use stock build-up, which is why the variation in inputs directly acts on the model output (old scrap). The ratio of Al going to the Building and Infrastructure application also exhibits some direct influence on the old scrap amount. For inputs into the Building and Infrastructure sector at the beginning of the modeling interval, practically no outputs are observed for a certain time. The tc_{sec} appears to have a bigger direct effect on old scrap generation than average lifetimes, but distinct trends are hard to identify since values for both groups of parameters fluctuate considerably over time.

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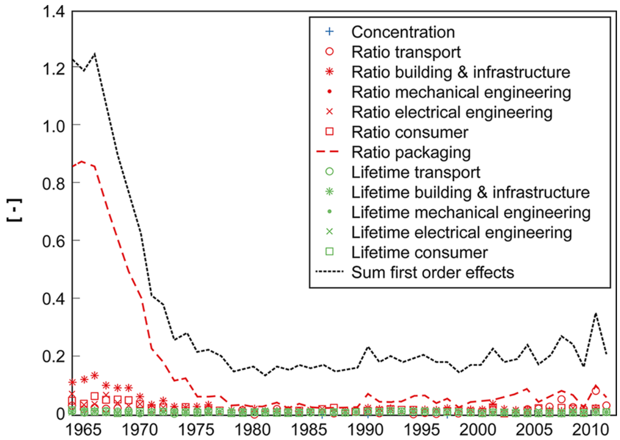

Figure 5. First order indices of national MFA model for the output variable total old scrap generation.

The direct effect of the Al concentration in final goods is low, which seems plausible considering that net imports originating from foreign trade of final products constitute only a small share of the total Al inputs to the use phase. In a nutshell, all parameters seem to have only small direct effects on the total generation of old scrap in our analysis. However, since parameter inputs are only contrasted with outputs of the same year, a full recovery of first order effects is not to be expected from the analysis. The decrease of the sum of all first order indices (Figure 5) in the first two decades results from the direct effect of packaging inputs on old scrap but is also an effect of model initiation. After about 10 years, the importance of direct effects decreases and interaction effects become an increasingly important factor in terms of total sensitivity. The level of 20% can be seen as a lower limit of first order effects, since an explicit consideration of inputs at previous time steps would increase the sum of first order effects.

The results indicate that a comprehensive understanding of sensitivities in (nonadditive) material flow models requires more sophisticated methods of global sensitivity analysis. Dynamic material flow models pose a specific challenge to the application of existing global sensitivity analysis, in particular due to the convolution of lifetime functions, which is implemented to model the residence time of products in the in-use stock. The time delays between inputs and outputs of the use phase make it difficult to interpret the variation of the output in a specific year as an effect of parameter variation in that year. In the present analysis, this is a minor issue for the initial years of the model, but it becomes a major limitation for the meaningful interpretation of the results for the later years, because the time-dependency of input and parameter values and the interrelationships with model outputs is not adequately reflected in the sensitivity analysis. Therefore, future work concerning parameter sensitivities should focus on simplified dynamic MFA systems (less flows, stocks, and parameters) in order to understand the interaction between parameters in a more mechanistic way and to identify feasible approaches of including the time dimension in such sensitivity analysis.

Model Uncertainty. As shown above, parameter uncertainties and sensitivities can be calculated using MCS, but model uncertainties[36] are not addressed in such analyses. In order to illustrate the effect of model uncertainty, a set of parameters is defined to consider EOL products, which do not leave the stock due to intended storage (e.g., hibernation) or the lack of incentives for disposal (e.g., obsolete cables in the ground). This extension of the stock in the model, results in a 7% decrease in the total old scrap flows compared to the original model, with the total in-use stocks increasing by 5% in 2012 (cf. Figure S6a,b, Supporting Information). Even though the magnitude of these effects depends on the estimated values of the parameters, they may also play a role in the observed difference between secondary production data and the modeled amount of scrap (cf. Figure 4d). While model uncertainty originating from EOL products not leaving the in-use stage is most influential at the end of the model period, effects from initial stock assumptions are most influential in the first decades of the model (cf. Figure S6c,d, Supporting Information). For instance, old scrap generation and in-use stock in 1990 are 11% and 6%, respectively, higher than the original model results. In 2012, the differences are as small as 1% and less than 1%, respectively, which shows that there is hardly any influence of initial stock assumptions on current in-use stocks and old scrap generation. However, this exercise highlights the importance of precise model structures and parameter definitions as another prerequisite for comprehensive uncertainty and sensitivity analysis in dynamic MFA models.

3.5. Final Remarks. In this work, we made a novel attempt to calibrate and verify a dynamic material flow model based on the extensive use of bottom-up estimates. Calibration was conducted for the in-use inputs into the transport and the packaging sector. Although calibration was only possible for 2 out of 6 in-use sectors, the results showed that (1) existing literature data on certain parameters (e.g., tc_{sec}) can deviate considerably compared to the calibrated parameter values (cf. Figure S1, Supporting Information) and (2) time-dependence of model parameters is an essential aspect in dynamic material flow modeling. Without calibration and the temporal adjustment of parameters, model results for individual sectors (e.g., in-use stocks, old scrap) may diverge substantially from well substantiated bottom-up estimates (cf. Figure 4), thereby not allowing for the assessment of current and potential future evolution of specific stocks. Because model calibration is limited to a few parts of the model due to the lack of data, cross-checks with bottom-up estimates on the remaining stocks and flows are essential for the verification of model results (cf. Figure 3). Analyses of the differences between model results and bottom-up estimates can be utilized for further investigation of model artifacts which are usually not explicitly addressed in dynamic material flow models (e.g., losses of Al scrap and production residues through landfilling). Dynamic top-down models could thus provide a complementary approach for assessing the amount of Al lost by landfilling over the last few decades.

Parameter uncertainties are evaluated using MCS. Variance-based analyses of global sensitivities (addressing parameter uncertainty) demonstrate that first order effects have only a minor influence on total variance of results in dynamic material flow models. Consequently, the often used "one-at-a-time" type of analysis has only limited explanatory power with respect to critical model parameters and their effect on the results. Although the sensitivity analysis could show that parameter interaction effects are important, the time-delayed relationships between model inputs and outputs pose a challenge to the present analysis, which complicates the interpretation of first order sensitivities over time. For a more comprehensive sensitivity analysis, an approach for explicitly considering time-dependent parameter variation is required. Calibration of model parameters based on bottom-up estimates is helpful to

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improve model reliability. Due to the extensive data demand for generating independent estimates, calibration is not possible for all relevant parameters. Due to the many parameter values potentially influencing a certain model result (i.e., flow or stock value), a selective informal approach of calibrating and cross-checking model results based on independent estimates is chosen. The presented approach makes use of available data to ensure model consistency, without requiring a degree of overdetermination such as would be the case for mathematically rigorous data reconciliation and rectification methods.

Concerning model uncertainty, a clear definition of the model structure and the parameters is crucial. The consideration of products not leaving the in-use stock after the end of their lifetime had a considerable effect on the calculated amount of scrap as well as on the size of the in-use stock. In contrast to that, initial stock assumptions do not really affect model results on old scrap generation and in-use stock past the year 2000. Uncertainties originating from imprecise or missing definitions of parameters are thus inherent in material flow models and are not captured by conventional analyses of (parameter) uncertainty.

From the comparison of national with aggregated (global) models, it can be stated that certain flows such as EOL export or exports of empty and filled packaging are potentially only captured on a national level since they are not reported in official (aggregated) statistics. Especially for countries within an open trade area (e.g., European Union), these flows are relevant in view of the total Al turnover. By means of calibration and cross-checks with bottom-up estimates, modeled trends of sector-specific stocks and flows are in good accordance with observed trends derived from independent sources (cf. Figure 4). Compared to "just" complying with the mass balance constraints of the model, this is a major step toward validated dynamic material flow models. On the one hand, this provides the opportunity to develop more precise models of future scrap flows integrating qualitative aspects, which are primarily depending on sector-specific Al applications. On the other hand, such models are indispensable to understand national Al consumption and scrap generation and utilization and serve as a basis to derive recommendations for administrative and regulatory authorities.

ASSOCIATED CONTENT

Supporting Information

Detailed model description, bottom-up calculations, and further results. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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Supporting Information

Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria

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Content:

1. Calculation method

A dynamic material flow model has been established in order to calculate Austrian Al flows and the evolution of stocks over the past 40 years. The model is roughly divided into five sub-stages namely, production, processing, manufacturing, in-use and waste management. Relevant trade flows are considered separately at the appropriate stage. A detailed description of the individual stages of the model, as well as information on input data (Sec. 2) and used model parameters (Sec. 3) is given below. For all stages pure Al is considered based on the average composition of various alloys. The values for Al contents of alloys are given in Table S2 based on literature data (Chen and Graedel, 2012, Liu and Müller, 2013, Sevigné-Itoiz et al. , 2014).

Production and unwrought metal trade

Concerning national Al production the processes of primary production and secondary production are considered. Although having in mind that on a global scale further upstream processes are relevant in order to supply primary Al industry with alumina processed from bauxite, these processes are not included since bauxite mining in Austria stopped in 1965 (Günther and Tichy, 1978). For primary Al production data is available until 1993, when production stopped in Austria and losses from the smelting of alumina are already considered in the reported data, since it is based on shipping amounts. Foreign trade of alumina is not considered explicitly, since a discrimination between alumina used for Al production and alumina used for technical ceramics is (historically) not possible from SITC rev.4. 285. Al flows induced by primary Al production are anyway captured through primary production data. Latest production data refers to national secondary Al industry, which experienced a considerable growth after the shutdown of primary production. Data on secondary Al production is again based on shipping amount and therefore not corrected for losses and the share of primary Al for dilution purposes, but production losses (dross and slag formation) these aspects are considered for the comparison of total scrap generation with secondary production in Sec. 4. In order to calculate total unwrought metal consumption at the production stage, trade data on unwrought Al are included at the production stage. Production data on ingot cast production as well as foreign trade of Al ingots is not reported separately, hence these processes are included in balancing the production process on a national scale. Foreign trade of Al Scrap is further considered, within the stage of production. Cross-checking in between the dataset compiled from various sources, as well as a cross-checking of model results with reported data has been conducted (Sec. 4), in order to evaluate the model quality and consistency.

Processing and semis-trade

Even though a detailed dataset for unwrought metal production has been established, semis production data is taken as the model driver, since trade data of semis can be easily linked to the distinct routes of semis production. Considered routes of semis production, as well as the considered trade flows are given in (Table S2). The trade flows are directly linked to the corresponding production routes, only trade flows from Al powder and flakes (SITC 68424) are excluded from the calculations, since Al in these applications is normally lost in terms of future recycling. Material yields from the processing of rollings, extrusions and castings are considered being 71%, 76% and 95% according to (Cullen and Allwood, 2013, Liu and Müller, 2013, Sevigné-Itoiz, Gasol, 2014, Svehla et al. , 2012). Material efficiency for castings processes seems to be high at the first sight, but is in accordance with a report on the Austrian casting industry (Svehla, Krutzler, 2012), which states that lost material is practically completely recycled internally. Foreign trade of semis is considered due to SITC codes given in Table S2. Data on national production of semis is mainly based on national statistics (Fachverband der Gießereiindutrie, 2010, Fachverband der NE-Metallindustrie, 2014, WBMS).

Manufacturing

Generation of fabrication scrap is considered with respect to sectors of application based on literature data (Cullen and Allwood, 2013, Hatayama, 2009, Liu and Müller, 2013)

Table S1. Material yields in manufacturing

	Transport	Building&infrastructure	Mechanical Eng.	Electrical Eng.	Consumer	Packaging
Material efficiency [%]	85	80	90	90	85	80

Foreign trade of semis is considered before manufacturing. After manufacturing the net imports of the trade code “Articles of Al (69979)” is added to each sector with respect to the given sector split (Sec. 3). Detailed information of the composition of SITC 69979 code is not available.

Trade of final products

A detailed list of considered trade flows including the allocation to the sectors and the average Al content is given in Table S2. The material concentrations in trade flows are determined through an extensive literature search and based on a previous work (Buchner et al. , 2014). Due to a time dynamic model the values of Al concentration in trade flows of transport application are adjusted according to development of the average Al content in vehicles (Ducker, 2011). Values in the table are corresponding the latest time period 2012-2002. Between 2001-1990 concentration values are lowered by 25% and between 1990-1964 Al concentration is again lowered by 25%. The position “Metal tanks, casks, drums, cans of Al” (SITC 69242) is included in the mechanical eng. as well as in the packging sector, since a certain amount of cans used for packing is presumably included in this category. The share of cans is calculated based on a comparison of data on trade new cans from the Austrian Recycling Association (ARA, 2013) with the comtrade dataset. A share of 75% cans in imports and 67% in exports is used in the model.

In-use

Finally annual inputs into in-use can be calculated by adding up flows from national manufacturing with net-imports of indirect Al flows from trade of final products separately for each end use sector. For the consideration of different lifetimes in each in-use sector sector-specific lifetime functions are defined based on the parameters given in Table S4. For the transport sector time dependent lifetime functions are defined with respect to a variable average lifetime. The packaging sector is split into two input flows. For the non-reusable part of packaging input, the output of every year equals the input. So no retention time is considered in the in-use stock. For the reusable part of the packaging input lifetime in the stock is considered due to the parameters given in Table S4.

Old scrap generation

Using sector specific lifetime functions for each sector, the output from in-use phase in subsequent years can be calculated. Average lifetimes and shape parameters of used lifetime functions are given in Table S4. The following effects are further considered for calculating the old scrap amount available for recycling from the output of in-use stock.

- **Export of used-vehicles**

  According to existing studies (Mehlhart et al. , 2011) trade on used vehicles has a great impact on the European vehicle market. Especially for Austria which neighbours Germany, the biggest used car exporter in Europe, and many Eastern European countries, the export of used vehicle gives high influence also concerning Al flows. Due to existing analysis (Kletzmayr, 2014a) about 75% of all deregistered passenger vehicles are exported. For commercial vehicles hardly any amounts of national disposal are recorded. Therefore between 2012-2002 and the rate of 70% for exported vehicle is chosen in the model, since passenger cars represent over 70% of national vehicle(Statistik Austria, 2011) fleet by number and the Al lost through exports of commercial vehicles has to be counterbalanced with Al recycled from repairing, dismantling which are both not determinable. Between 2001-1995 the rate of exported vehicles is set to 45% and before 1995 to 20%, since it is assumed that car exports have increased considerably after the entry of Austria in the European Union in 1995, even though no concrete data is available. The amount of shredded passenger vehicles are recorded and compared with modelled national old scrap in the transport sector.

- **Collection and loss rate transport**

  The loss rate in our model definition combines two effects; the collection losses which occur from EOL material which is not collected and processing losses which occur through the processing of old scrap. A detailed description and definition on recycling rates is given in (Chen, 2013). The loss rate of Al outputs from transport application is set to 2% due to actual loss rates of national shredders (Kletzmayr, 2014a) being the major processor of EOL vehicles in Austria.

- **Collection and loss rate packaging**

  Loss rates on packaging are by far more difficult to determine than for transport application, since collection routes of Al packaging waste are diverse (municipal solid waste (MSW), separate collection) and processing rates are heavily depending on the actual processing route. Hence, a bottom-up approach is used for defining the loss rate of Al old scrap. Therefore the total annual amount of Al nationally consumed for packaging which is recorded by the Austrian Recycling Association (ARA) (ARA, 2013) is compared with the amount of separately collected packaging Al + the amount of Al recovered Al from MSW processing (incineration, mechanical processing). The total amount of Al recovered from MSW is corrected by the input ratio of packaging and non-packaging Al inputs available from previous studies (Taverna et al. , 2010). The loss rate of Al from packaging application is set to 65% in the model.

- **Collection and loss rate other sectors**

  For the remaining sectors loss rates are not determinable by bottom-up data, hence existing literature data (Liu and Müller, 2013, Sevigné-Itoiz, Gasol, 2014) has been used in order to consider losses for these sectors. But since high losses for packaging waste are considered explicitly in our model the average numbers from literature are adjusted downwards. Losses for the remaining in-use sectors (building&infrastructure, mechanical eng., electrical eng. and consumer) are set to 5%.

2. Model data

Data concerning primary and secondary production has been compiled from various data sources since no single continuous dataset is available. Data for semis production is reported by (WBMS) and national industrial unions in younger history (Fachverband der Gießereiindutrie, 2010, Fachverband der NE-Metallindustrie, 2014). Values for trade of semis are taken from the UN comtrade database which shows good accordance with national trade statistics.

Table S2. Production input data and trade flows

	Type	**SITC 1[1], SITC 2[2], SITC 3[3]**	**Source**	**Al Concentration [%]**	**Source**
Production					
Prim Al. Production	Prod		(Aiginger et al. , 1986, WBMS)	99.7	(Liu et al. , 2011)
Secondary Al. Production	Prod		(Aiginger, Bayer, 1986, Fachverband der NE-Metallindustrie, 2014, WBMS)	97	(own estimation)
Unwrought Al	Trade	6841[1-2] 68411[3] 68412[3]	(Comtrade, 2014)	99.7	(Liu, Bangs, 2011)
Al Scrap	Trade	284[1] 28823[2-3]	(Comtrade, 2014)	90	(own estimation)
Semis-Processing					
Rolling	Prod		(Fachverband der NE-Metallindustrie, 2014, WBMS)	95	(Liu, Bangs, 2011)
Extrusion	Prod		(Fachverband der NE-Metallindustrie, 2014, WBMS)	95	(Liu, Bangs, 2011)
Casting	Prod		(Fachverband der Gießereiindutrie, 2010, WBMS)	90	(Liu, Bangs, 2011)
Bars, rods, angles, shapes an wire of Al	Trade	68421[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Plates, sheets and strip of Al	Trade	68422[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Al foil	Trade	68423[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Al powders and flakes	Trade	68424[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Tubes, pipes and blanks, hollow bars of Al	Trade	68425[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Tube and pipe fittings of Al	Trade	68426[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Al tube and pipe fittings	Trade	68427[1-3]	(Comtrade, 2014)	95	(Liu, Bangs, 2011)
Manufacturing					
Articles of aluminium	Trade	69894[1] 69979[3]	(Comtrade, 2014)	90	(own estimate)

Trade of final goods is based on comtrade statistics. For incomplete data series national statistics have been used to fill data gaps. Classification refers to the *Standard International Trade Classification* whereas the datasets have been extracted as reported. Classification of data changed over time and therefore the Trade Classification has been revised several times up to now. Since the single codes are taken "as reported" some categories with similar or identical names can be observed, which just means that the associated SITC code changed over time. The corresponding SITC versions to each product category are given in Table S3. Assumed average Al contents are shown and are assumed equal in imports and exports.

Table S3. Input data for trade of final products

	SITC 1[1] **SITC 2[2]** **SITC 3[3]** **SITC 4[4]**	**Al Concentration[%]**	**Source**
Transport			
Internal combustion piston engines and parts thereof	7115[1], 713[2-3]	25	(Klüting and Landerl, 2004)
Passenger motor vehicles (excluding buses)	781[2-3]	8	(Ducker, 2011)
Lorries and special purposes motor vehicles	782[2-3]	6	Based on (Liu and Müller, 2013)
Road motor vehicles	783[2-3]	6	(SCA, 2010)
Motor vehicle parts and accessories	784[2-3]	10	Estimated based on 713
Cycles, scooters, motorized or not	785[2-3]	10	(SCA, 2010)
Trailers and other vehicles, not motorized	786[2-3]	10	Based on (Bouzidi and Leymarie, 2009)
Railway vehicles and associated equipment	791[2-3]	1	(SCA, 2010)
Aircraft and associated equipment and parts thereof	792[2-3]	13	(SCA, 2010)
Ships, beats and floating structures	793[2-3]	2	(SCA, 2010)
Passenger motor cars, other than buses	7321[1]	8	(Ducker, 2011)
Buses, including trolleybuses	7322[1]	8	Based on (Bouzidi and Leymarie, 2009)
Lorries and trucks	7323[1]	6	Based on (Bouzidi and Leymarie, 2009), (Liu and Müller, 2013)
Special purpose lorries, trucks and vans	7324[1]	6	Based on 7323
Road tractors for tractor trailer combinations	7325[1]	6	Based on 7323
Chassis with engs. mntd. for vehicles of 732.1	7326[1]	6	Based on 7323
Other chassis with engines mounted	7327[1]	6	Based on 7323
Bodies & parts motor vehicles (ex. motorcycles)	7328[1]	6	Based on 7323
Motorcycles, motorized cycles and their parts	7329[1]	5	Own estimation
Road vehicles other than motor vehicles	733[1]	1	Own estimation
Building & Infrastructure			
Fin. Structural parts& structures of aluminium	6912[1-3]	90	(own estimate), (Liu and Müller, 2013)
Mechanical Engineering			
Power generating machinery, other than electric	711[1]	1	Own estimate
Agricultural machinery	712[1]	1	(SCA, 2010)
Other machines	714[1]	5	(SCA, 2010)
Special machinery	717[1]	2	(SCA, 2010)
Machines for special industries	718[1]	2	(SCA, 2010)
Machinery and appliances non electrical parts	719[1]	3	(SCA, 2010)
Agricultural machinery and parts thereof	721[2-3]	1	(SCA, 2010)
Tractors	722[2-3]	1	(SCA, 2010)
Civil engineering and contractor's plant and equipment and parts thereof	723[2-3]	5	(Recalde et al. , 2008)
Textile and leather machinery and parts thereof	724[2-3]	1	(Recalde, Wang,

			2008), (SCA, 2010)
Paper mill and pulp mill machinery	725[2-3]	2	(SCA, 2010)
Printing bookbinding machinery and parts thereof	726[2-3]	2	(SCA, 2010)
Food-processing machines (excluding domestic); parts thereof	727[2-3]	1	(SCA, 2010)
Other machinery and equipment specialized fo particular industries and parts thereof	728[2-3]	2	(SCA, 2010)
Machine-tools for working metal or metal carbides and parts and accessories thereof	736[2]	2	(SCA, 2010)
Metalworking machinery (other than machine-tolls) and parts thereof	737[2-3]	1	(SCA, 2010)
Heating and cooling equipment and parts thereof	741[2-3]	2	(SCA, 2010)
Pumps for liquids	742[2-3]	2	(SCA, 2010)
Pumps and compressors	743[2-3]	6	(SCA, 2010)
Mechanical handling equipment and parts thereof	744[2-3]	1	Own estimate
Other non-electric machinery, tools and mechanical apparatus and parts thereof	745[2-3]	1	Own estimate
Transmission shafts and cranks	748[2-3]	2	Own estimate
Non-electric parts and accessories of machinery	749[2-3]	2	Own estimate
Textile and leather machinery	717[1]	2	(Recalde, Wang, 2008), (SCA, 2010)
Machinery and appliances (non electrical parts)	719[1]	3	Own estimate
Metal Reservoirs, Tanks, Vats And Similar Containers With A Capacity Of Over 300 Liters, Of Aluminum	6921[1-2], 69212[3]	90	(Liu and Müller, 2013, SCA, 2010)
Metal Tanks, Casks, Drums, Cans And Similar Containers With A Capacity Of Not Over 300 Liters, of Aluminum	6924[2], 69242[3]	90	(Liu and Müller, 2013, SCA, 2010)
Metal Containers For Compressed Air Or Liquefied Gas, of Aluminum	6924[2], 69244[3]	90	(Liu and Müller, 2013, SCA, 2010)
Stranded Wire, Ropes, Cables, Etc. of Aluminum, not Electrically Insulated	69313[2-3]	90	(Liu and Müller, 2013)
Electrical Engineering			
Rotating electric plant and parts thereof	716[2-3]	2	Own estimate
Electric power machinery and switchgear	722[1]	3	Own estimate
Equipment for distributing electricity	723[1]	2	Own estimate
Electrical apparatus for medic purpose, radiological applic.	726[1]	2	Own estimate
Other electrical machinery and apparatus	729[1]	3	Own estimate
Electric power machinery and parts thereof	771[2-3]	16	(SCA, 2010)
Electrical apparatus for making and breaking electrical circuits	772[2-3]	2	Based on 771
Equipment for distributionof electricity	773[2-3]	2	Based on
Electro-medical and radiological equipment	774[2-3]	2	Own estimate
Optical instruments and apparatus	871[2-3]	2	Own estimate
Medical instruments and appliances	872[2-3]	2	(Liu and Müller, 2013)
Meters and counters	873[2-3]	2	Based on (SCA, 2010)
Measuring, checking, analysis, controlling instruments	874[2-3]	2	Based on (SCA, 2010)
Thermionic, microcircuits, transistors, valves etc.	776[2-3]	2	estimate based on 763, 752
Electrical machinery and apparatus	778[2-3]	2	estimate based on 763, 752
Other electric conductors, for a voltage not > 1kV	7731[1-3], 77316[4]	30	Estimate based on (Centrovox, 2013)
Other electric conductors, for a voltage not < 1kV	7731[1-3], 77317[4]	50	Estimate based on (Centrovox, 2013)
Other electric conductors for a voltage 80V – 1kV	7731[1-3], 77315[4]	30	Estimate based on (Centrovox, 2013)
Consumer			
Base metal domestic articles and parts thereof; of Al	69743[2-3]	90	Own estimate
Base metal indoors sanitary ware and parts thereof; of Al	69753[2-3]	90	Own estimate
Telecommunication apparatus	724[1]	3	Based on 751, 764
Domestic electrical equipment	725[1]	3	Own estimate
Office machines	751[2-3]	5	(Salhofer and Tesar, 2011, SCA, 2010, Truttmann and Rechberger, 2006
Automatic data processing machines and units thereof	752[2-3]	5	(Salhofer and Tesar, 2011, SCA, 2010,

			Truttmann and Rechberger, 2006
Parts, nes of and accessories for machines of heading 751,752	759[2-3]	5	(Salhofer and Tesar, 2011, SCA, 2010, Truttmann and Rechberger, 2006)
Television receivers	761[2-3]	2	(Truttmann and Rechberger, 2006)
Radio-broadcast receivers	762[2-3]	6	(Truttmann and Rechberger, 2006)
Gramophones, dictating machines and other sound recorders	763[2-3]	2	(Truttmann and Rechberger, 2006)
Telecommunication equipment, nes; parts and accessories nes	764[2-3]	2	(Truttmann and Rechberger, 2006)
Household type equipment, nes	775[2-3]	2	(Salhofer and Tesar, 2011) (SCA, 2010)
Packaging			
Metal Tanks, Casks, Drums, Cans And Similar Containers With A Capacity Of Not Over 300 Liters, of Aluminum	69242[2-3]	90	Own estimate

3. Model parameters

Al concentration in final goods:

Values of Al concentration in final goods are set according to previous studies and literature data (Buchner, Laner, 2014, Liu and Müller, 2013, SCA, 2010) and listed in Table S3. Values given in Table S3 refer to the year 2012. Adjustments in concentrations over time have only been made for transport applications since trends of Al usage in vehicles are available from literature (see also Section 1). The relative standard deviation is set to an average value of 30% assuming normally distributed variables. Concentration values in the Monte Carlo Simulations are sampled from a normal distribution.

Sector split ratios:

Historical sector split ratios on Al production with respect to end uses are available from statistics (WBMS). Since these ratios are not constant over time and existing literature data on sector split ratios are often not plausible, a calibration with bottom-up data has been conducted for the transport and packaging ratios. Bottom-up inputs for the transport sector derived from the recorded registrations (Statistik Austria, 2011) of all types of vehicles multiplied with a time-depended average Al content per vehicle (Ducker, 2011). For adjustment of Al content the development in passenger cars is taken are representative for the whole vehicle fleet. The inputs into the packaging sector are yearly recorded by the ARA and where readily available back to 1998. Calibration has been conducted by linear optimization between modelled inputs using literature sectors splits and inputs from bottom-up calculations. After calibrating for packaging and transport the remaining sectors are adjusted proportionally to the historical values. The adjusted trends of the sector split ratios over time is given in Figure S1a.

Lifetime distribution functions:

Weibull functions are chosen for describing the residence time of Al in various applications. Definition of the Weibull probability density functions is used according to Formula S1. Both, the scale parameter *a*, average lifetime, and the shape parameter *b*, are set according to literature values (Chen and Graedel, 2012, Dahlström et al. , 2004b, Liu and Müller, 2013, Melo, 1999). Only for the transport sector a time-dependent average lifetime (*a*) could be derived from bottom-up calculations (see below). For other sectors time-depended average lifetimes are not available, even though they might as well vary over time, e.g. premature replacement of electronic products due to the change from CRT to LCD displays.
Shape parameters are also chosen due to literature values (Dahlström et al. , 2004a), but as existing studies show, average lifetimes are by far more influential on model outputs than the shape of the chosen distribution (Melo, 1999).

$$f(x|a,b) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-(\frac{x}{a})^b} \qquad \text{(S1)}$$

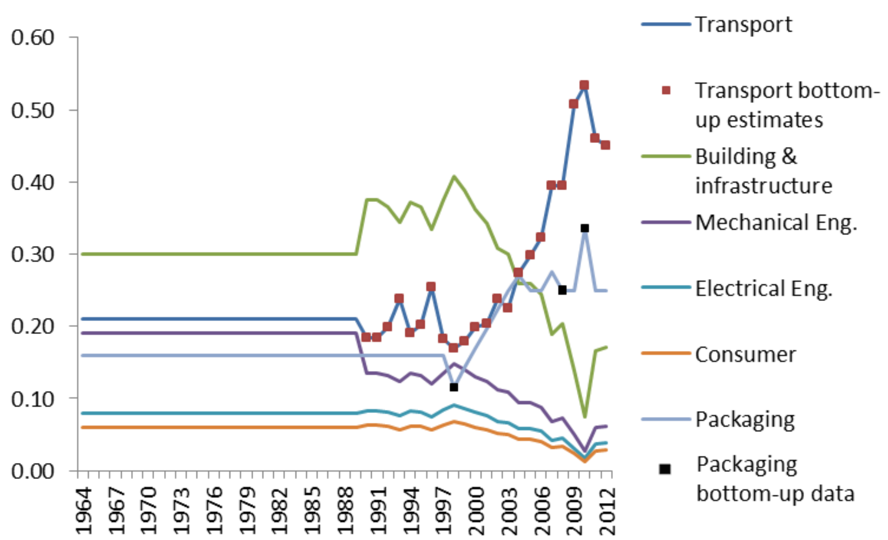
Table S4. Values and uncertainty ranges for uncertainty calculation

	Al concentration final goods	Ratio Transport	Ratio Building& Infrastructure	Ratio Mechanical Eng.	Ratio Electrical Eng.	Ratio Consumer	Ratio Packaging	Lifetime Transport	Lifetime Building& Infrastructure	Lifetime Mechanical Eng.	Lifetime Electrical Eng.	Lifetime Consumer	Lifetime Packaging (re-use)
Value	Tab. S2	Fig. S1	Fig. S1	Fig. S1	Fig. S1	Fig. S1	Fig. S1	-	-	-	-	-	-
Standard deviation (relative)	30%	20%	20%	20%	20%	20%	20%	10%	30%	20%	20%	15%	10%
Scale parameter (Weibull)	-	-	-	-	-	-	-	Fig S2	40	17	25	10	3
Shape parameter (Weibull)	-	-	-	-	-	-	-	3	3	3	3	3	3

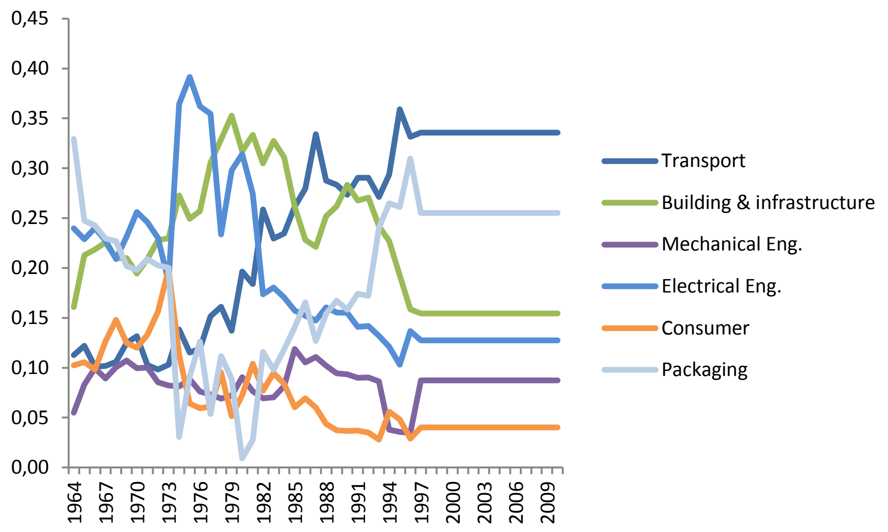
Calibration of sector split ratios

Starting in 1990 a calibration of model parameters using bottom-up data is conducted for the transport and the packaging sector. Bottom-up data are available for the packaging sector starting from the year 1998. Although the rigorous calibration of model parameters with bottom-up data results in non-smooth curves for the sector split rations over time (cf. Figure S1), the trends for the sectors can be derived quite well from the calibration. Figure S1 is therefore more intended to display the possibility of calibration and secondly the even more important aspect how significantly ratios can change over time. In input driven models ratios at the beginning of the model period don't display high effects on the results at the end of the modelling period, although also these effects are depending on the lifetime of the in-use sectors. But at the end of the modelling the time-dependent adjustment of sector split ratios become more and more important in order to fit the trends of the model to the existing trends in reality.

For the comparison of the calibrated sector splits used in this model (Figure S1a) with literature data, WBMS data on sector splits is shown in Fig. S1b. Since semis where used as the model driver in this study, some categories of WBMS statistics do not exist in this study. These categories in WBMS data are proportionally allocated to the other sectors of WBMS data in order to achieve comparability with the sector splits of this model. Proportionally means that the "other" category is added to the other sectors according to their original shares, in order to derive a distribution of six in-use sectors like it is used in this model. Even though high fluctuations of historical sector splits are not explainable, long term trends of our calibrated sector splits are supported by literature data. For the years after 1997 no literature data is available (constant values are assumed in WBMS).



a)



b)

Figure S1. Calibrated and adjusted sector split ratios (top) used in this model; adjusted literature data (bottom)

Time-dependent lifetimes (transport sector)

Time dependent average lifetimes are difficult to obtain, since they are difficult to verify. Especially the often used average age of products in a certain in-use stock seem not to be very appropriate as a measure of average lifetimes in input oriented models, since average lifetimes with respect to stocks are heavily influenced by the inputs and outputs of the stock. For example, if inputs in a stock are high over a certain period, average age of articles in the stock will decrease. Also an enhanced output from a stock, for example caused by a technical change (CRT -> LCD displays) could decrease average lifetime in the stock. So no direct link is possible from average age in stocks to lifetimes of inputs in a certain year, which are required for computing input oriented models. This is also the reason, why the measure of car longevity (Feeney and Cardebring, 1988, Söderberg, 2014) seems to be an inappropriate measure for average lifetimes with respect to input oriented material flow models.

For the Austrian model the average lifetime in the transport sector are determined by observations of car age at scrappage (Kletzmayr, 2014a) and the average age of exported cars (Mehlhart, Merz, 2011). A summary of the calculations for average lifetime is given in Table S5.

Table S5. Calculation of average car age

Exported cars		Shredded cars	
Vehicle age [yr.]	Number	Vehicle age [yr.]	Number
7	129.333	17.63	71.000
11.5	32.333		
15	32.333		
Σ	194.000	Σ	71.000
Average age [yr.] (2012)		**14.30**	

Knowing the average age of cars leaving in-use phase in 2012 this average lifetime is shifted by the calculated average lifetime to 1998, since it represents the average residence time of a car entering 1998. From (Kletzmayr, 2014a) data on the average age of shredded cars between 2006 and 2012 is available, which shows (interpolated) average increase of about 1% per year. Since no other data is available, this trend is extrapolated in the period from1992 to 2012. Before 1992 a constant average lifetime is assumed (Figure S2).

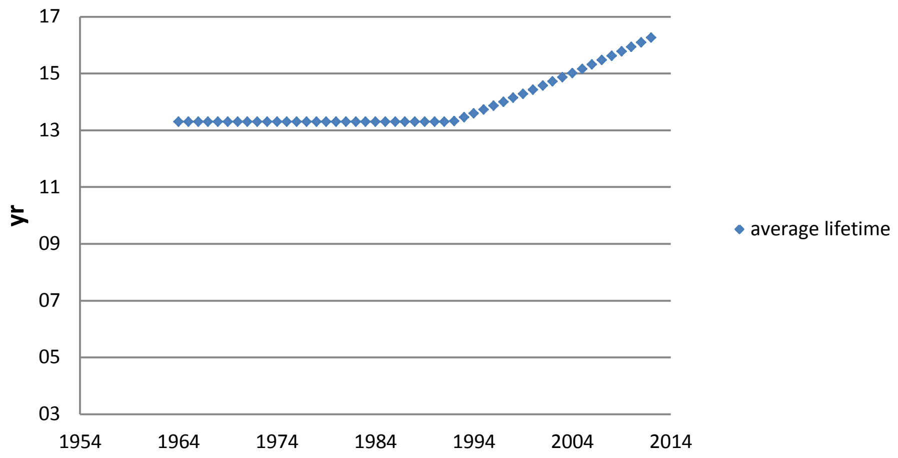


Figure S2. Time dependent avg. lifetime for the transport sector

4. Bottom-up data

Road vehicles:

Vehicle categories and time-dependent Al concentration used for bottom-up calculations of the transport stock and inputs are given in Table S6 and Table S7. Categories of vehicles are in correspondence to official statistics (Austria, 1990-2012a, b), Al contents (Ducker, 2011, EAA, 2012) are timely adjusted by the half of the average lifetime (8 years) in order to approximate the real average Al content of vehicles in the in-use stock. For example, the average Al-content of a new car in 2004 is considered to be the average Al content of in-use cars in the year 2012. Al contents in main categories of commercial vehicles (trucks, buses etc.) are adjusted proportionally to the penetration of Al in passenger cars, since no historical data on Al contents is available. For special categories like working machines, small motor vehicles the Al content is kept constant due to a lack of (historical) information. Al contents of different types are derived from literature (Buchner, Laner, 2014, Ducker, 2011, Mathieux and Brissaud, 2010, Recalde, Wang, 2008) and partly based on model assumption for special vehicle categories.

Table S6. Al concentrations for different types of vehicles used for bottom-up calculations of transport in-use stock

	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992
Passenger cars																					
Gas	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	47
Diesel	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	47
Electric	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
Liquid gas	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48
Natural gas	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48
Gas/ Liquid gas (bivalent)	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48
Gas/Natural gas (bivalent)	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48
Gas/Electric (hybrid)	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48
Diesel/Electric (hybrid)	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62	59	56	53	50	48	48

Motor-Bike Kl. L3e [1)]	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Motor-Bike Kl. L1e	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
4-Wheel motor vehicles Kl. L7e	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Motor-Bike Kl. L3e	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
3-Wheel motor vehicles Kl. L5e	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
3-Wheel motor vehicles Kl. L2e	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Light 4-wheele vehicles Kl. L6e	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Light Motor bikes Kl. L3e [2)]	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Buses Kl. M2 and M3	837	800	763	726	689	654	620	585	551	517	495	474	453	432	411	392	374	355	336	318	300
Trucks																					
< 3,5t gross vehicle weight	223	220	217	213	210	207	204	201	198	195	192	189	186	183	180	178	176	175	173	171	169
3,5t - 12t gross vehicle weight	373	360	347	334	320	308	296	284	271	259	251	243	235	226	218	212	205	198	192	185	178
> 12t gross vehicle weight	523	500	477	454	430	409	387	366	344	323	310	296	283	270	257	245	234	222	211	199	187
Tractor	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
Tractor with semi-trailer	262	250	238	227	215	204	194	183	172	161	155	148	142	135	128	123	117	111	105	99	93
“Motor- und Transportkarren”	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Work machines	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Harvesting machines	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
Caravans	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Other vehicles	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
Trailers																					
Trailors Kl. O und R	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Agricultural trailers	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Caravan trailers	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Working machines trailers	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Special trailers	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Table S7. Al concentrations for different types of vehicles used for bottom-up calculations of transport in-use input

	2012	**2011**	**2010**	**2009**	**2008**	**2007**	**2006**	**2005**	**2004**	**2003**	**2002**	**2001**	**2000**	**1999**	**1998**	**1997**	**1996**	**1995**	**1994**	**1993**	**1992**	**1991**	**1990**
Passenger cars	150	149	146	143	140	138	135	132	126	121	115	110	104	99	94	88	83	78	75	72	68	65	62
Trucks	621	617	604	593	581	570	558	546	523	500	477	454	430	409	387	366	344	323	310	296	283	270	257
Buses	993	987	967	948	930	911	893	874	837	800	763	726	689	654	620	585	551	517	495	474	453	432	411
Semitrailor tractor	310	308	302	296	291	285	279	273	262	250	238	227	215	204	194	183	172	161	155	148	142	135	128
Working machines	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
Light vehicles	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Motor bikes (light motor bikes)	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Small motor bikes	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Mopeds	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Trailers	250	248	243	239	234	229	225	220	211	201	192	183	173	165	156	147	139	130	125	119	114	109	103

Airplanes, Railways and Ships:

Bottom-up data on aluminium use in rail vehicles, aircrafts and ships (Table S8) is evaluated in order to compare the total bottom-up transportation stock to the calculated and modelled stock of road vehicles. Bottom-up calculations on rail vehicles, aircrafts and ships are based on (Buchner, Laner, 2014). Al-contents are for these types of vehicles are generally difficult to obtain, since they are hardly documented. Moreover, categories of types of vehicles are not differentiated very well in inventory statistics. Therefore Al-contents are mainly based on literature values and in case of unavailable data based on own estimations. For rail vehicles and aircrafts official data from Statistics Austria is available, not so for the inventory of ships. In order to estimate the ship inventory, the registered passenger and commercial ships are considered.

Table S8. Al-concentration and bottom-up calculation on railroad, airplane and ship inventory

	Quantity [number]	Al content [kg]	Source	Total Al [t]
rail vehicles				
electric locomotive	889 (Statistik Austria, 2013a)	**1,640**	own estimation based on (Recalde, Wang, 2008, SCA, 2010)	1,500
diesel locomotive	520 (Statistik Austria, 2013a)	**328**	own estimation based on (Recalde, Wang, 2008, SCA, 2010)	170
railcars	645 (Statistik Austria, 2013a)	**12,600**	own estimation based on (Recalde, Wang, 2008, SCA, 2010)	8,100
passenger wagon	2,524 (Statistik Austria, 2013a)	**600**	own estimation based on (Recalde, Wang, 2008, SCA, 2010)	1,500
aircrafts				
< 5,700 kg	817 (Statistik Austria, 2013c)	**1710**	Own estimation[1]	1,4
5,700-20,000 kg	132 (Statistik Austria, 2013c)	**4,320**	Own estimation[2]	570
> 14,000 kg	185 (Statistik Austria, 2013c)	**24,000**	Own estimation[3]	4,400
other aircrafts	207 (Statistik Austria, 2013c)	**1710**	Own estimation[1]	350
ships				
Passenger ships				
< 12 passengers	175 (Statistik Austria, 2003b)	**100**	Own estimation[4]	175
13-20 passengers	9 (Statistik Austria, 2003b)	**100**	Own estimation[4]	0,9

21-30 passengers	21 (Statistik Austria, 2003b)	**100**	Own estimation[4]	2,1
31-50 passengers	16 (Statistik Austria, 2003b)	**2,400**	Own estimation[5]	39
51-75 passengers	15 (Statistik Austria, 2003b)	**2,400**	Own estimation[5]	36
76-100 passengers	20 (Statistik Austria, 2003b)	**2,400**	Own estimation[5]	48
101-150 passengers	19 (Statistik Austria, 2003b)	**9,000**	Own estimation[6]	170
151-200 passengers	26 (Statistik Austria, 2003b)	**9,000**	Own estimation[6]	230
> 200 passengers	30 (Statistik Austria, 2003b)	**9,000**	Own estimation[6]	270
Commercial ships				
< 649 t carrying capacity	31 (Statistik Austria, 2003a)	**1,700**	Own estimation[7]	53
650-999 t carrying capacity	5 (Statistik Austria, 2003a)	**3,400**	Own estimation[7]	17
1,000-1,499 t carrying capacity	16 (Statistik Austria, 2003a)	**4,700**	Own estimation[7]	75
> 1,500 t carrying capacity	90 (Statistik Austria, 2003a)	**30.000**	Own estimation[7]	2,700
Total				**20,400**

[1] Unit weight 2,850 kg, 60weight% Al estimated based on (Boeing, 2015, Liu and Müller, 2013)
[2] Unit weight 7.200 kg, 60weight% Al estimated based on (Boeing, 2015, Liu and Müller, 2013)
[3] Unit weight 40.000 kg, 60weight% Al estimated based on (Boeing, 2015, Liu and Müller, 2013)
[4] Unit weight for ships 1 - 30 passengers 2.000kg (www.mastercraft.com), 5% Al estimated based on (Recalde, Wang, 2008, SCA, 2010)
[5] Unit weight for ships 31 - 100 passengers 80 t (own estimation), 3% Al estimated based on (Recalde, Wang, 2008, SCA, 2010)
[6].Unit weight for ships 100 - >200 passengers 300t (own estimation) 3% Al estimated based on (Recalde, Wang, 2008, SCA, 2010)
[7] Unit weight calculated based on average carrying capacity for each category (Zöllner, 2009), 2% Al estimated based on (Recalde, Wang, 2008, SCA, 2010)

From the comparison of the different categories of vehicles, it is apparent that non-road vehicles represent only a very small share of the total transportation Al stock, contributing only 2% to total transport in-use stock. Results are fairly reasonable since there is only one minor international flight company operating in Austrian and because of Austria’s continental location in Europe shipping is more or less limited to inland transportation. Currently there is no international ship registered in Austria (bmvit, 2014) and the share of ship transports of total transport volume in Austria is about 2,5% by weight (Statistik Austria, 2013b).

Power grid network:

Al-content of the power grid network is calculated based on documented systems length for all levels of voltage (E-Control, 2011). Since the operation of the power grid network in Austria is carried out by various operators according to the nine federal states in Austria and separate countrywide transmission grid operators the data of Al content per km is derived from personal conversation to one local operator and a transmission grid operator. The ratio between open wire lines and cabling as well as diameters of the used cables and wires are considered in the given Al contents per km. Al-content of additional facilities like transformer stations etc. is also based on personal information (APG, 2013, Energie AG, 2013).

Table S9. Al-concentration and bottom-up calculation of the power grid network based on system lengths in 2011

	System length [km]	Al per km [t]	Total Al [t]
Low voltage (400/980 V)	166,746	1.21	201,245
Middle voltage (6/10/20/30/60 kV)	68,136	0.95	64,729
High voltage (110 kV)	11,084	3.2	35,470
High voltage (220-380 kV)	6,506	7.68	50,000
Transformer stations etc.			1,700
Total			**353,144**

5. Calibrated input flows (transport, packaging)

Calibrated input flows for the transport (Fig. S3, top) and packaging sector (Fig. S3, bottom), based on adjusted tc_{sec} (cf. Sec. 3). For the period before 1998 information on Al consumed for packaging is poor. The distinct increase of Al manufactured for packaging between 1995 and 2003 is mainly due to a considerable growth in the export-oriented Austrian beverage industry, which is documented by bottom-up data.

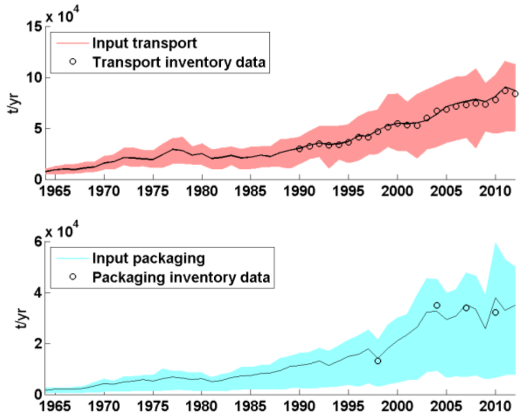


Figure S3. Calibrated Al inputs into in-use for transport (top) and packaging application (bottom). Bottom–up data for individual years is indicated (loops).

6. Detailed results on scrap flows

Trends in national scrap generation are shown in Figure S4. Processing scrap and manufacturing scrap increase steadily over time, which is in accordance with the increasing outputs of the national Al industry. A more pronounced increase can be seen for the Al old scrap amount during the last 30 years. Total recycle able old scrap generated is about 70% of new scrap generation (from processing and manufacturing). Significant increases are observed for net-scrap imports, especially over the past 5 years (cf. Figure S4a). Even though an increase in national production capacities is observed over this period, some other factors (which are still under investigation) must play a role, because the whole increase in net-imports cannot be explained solely based on the increase of production capacity. Total new scrap generation shows a nearly linear increase over time (Figure S4b). Scrap from extrusion is shows the biggest relative increase (due to increasing production capacities). The amount casting scrap shown refers only to the share of scrap which is discarded from foundries and not remelted internally. The breakdown of manufacturing scrap (Figure S4c). is clearly influenced by the chosen sector split ratios. Which means, that even though the sum of manufacturing scrap delivers a quite reasonable trend, the knowledge of scrap shares originating from distinct applications is limited by the knowledge on sector split ratios.

In FigureS4d the total amount of old scrap available for recycling, after considering vehicle exports and losses from collection and processing, is shown. Losses from vehicle exports are considered due to rates given in Sec. 1, for consumer products including WEEE an illegal export of 15% is considered (Sander and Schilling, 2010), losses of packaging material are set to 60% due to bottom-up calculations, losses for transport are set to 2% (Kletzmayr, 2014b) and losses for all other sectors are set to 5% .

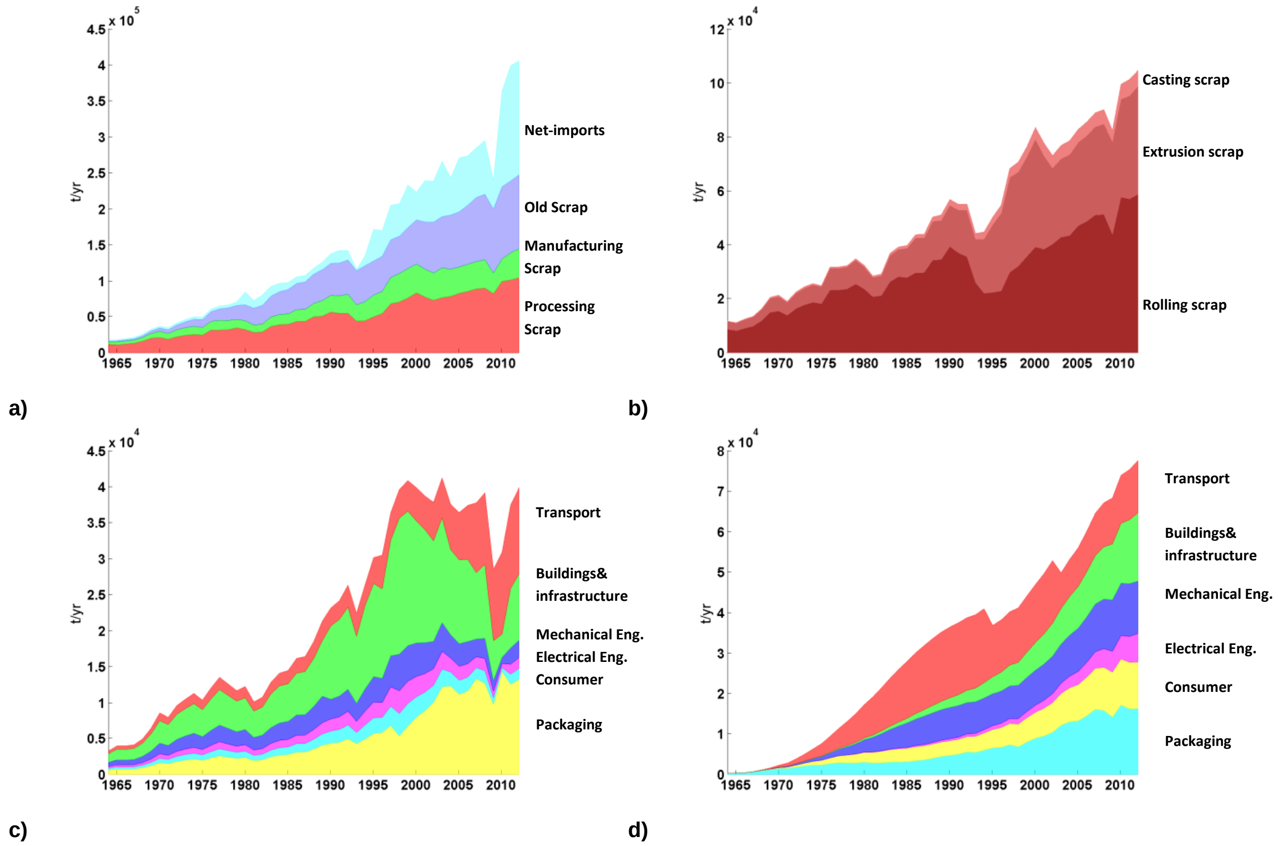


Figure S4. Generated total, new and recyclable old scrap amounts over time. a) Total Austrian scrap generation + net-imports; b) Processing scrap generation; c) Manufacturing scrap generation with respect to in-use sectors; d) Old scrap generation excl. vehicle-exports

7. Cross-checking of input data

Since the data on primary and secondary production, as well as foreign trade of unwrought metal and semis production is not available from one data source, a model data set has been compiled. As mentioned in Sec. 1 the national production of semis is chosen as the model driver. In order to check the plausibility and consistence of the overall balance a cross-check of input data is performed using Eq. S2. Therefore the consumption of unwrought Al is calculated in an upstream (prim + sec. production + net imports of unwrought metal) and a downstream direction (semis production + processing scrap). As shown in

Figure S5 a good accordance of input data with model results is achieved in our model. An average addition of 15% primary Al is considered for secondary production (Buchner, Laner, 2014, Fachverband der NE-Metallindustrie, 2014).

$$prim\_production_i + \mathbf{sec\_production_i} * 0.85 + net\ import\ unwrought\ Al_i = semis\ production_i + fabrication\ scrap_i \quad \text{(S2)}$$

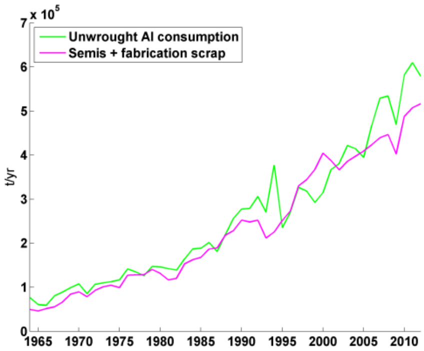


Figure S5. Unwrought metal consumption vs. semis production + processing scrap

8. Analysis of the model uncertainty

Effects of Al not leaving in-use:

In order to display the effect of model uncertainty, which is normally not explicitly addressed in exiting MFA studies, the actual model is once run without any parameters considering hibernation and obsolescence in in-use stock and once run with a sample set of parameters. For the transport sector a rudimental analysis has been conducted in order to calculate a

feasible rate for Al not leaving in-use after average lifetime. Calculating with 5% ratio of products not leaving transport stock results in a 4.5% lower transport stock in 2012, compared to neglecting these accumulations in stock. Inventory data on the Austrian vehicle fleet shows about 10% of vehicle above 25 years (Statistik Austria, 2011). Being aware that not all vehicles over 25 year are out of use, our estimates of 5% are considered being a feasible estimate.
For the packaging sector the main share of Al is considered leaving in-use stock in the same year, therefore the corresponding value is set to zero. For all other sectors no recorded and no literature data is available for considering the effects of hibernation and obsolescence explicitly by inducing parameters in the model. Hence, rates for the other sectors are estimated (Table S10) with the main goal to illustrate the effects of not scrapped Al on the model outputs and the implication on model uncertainty. In

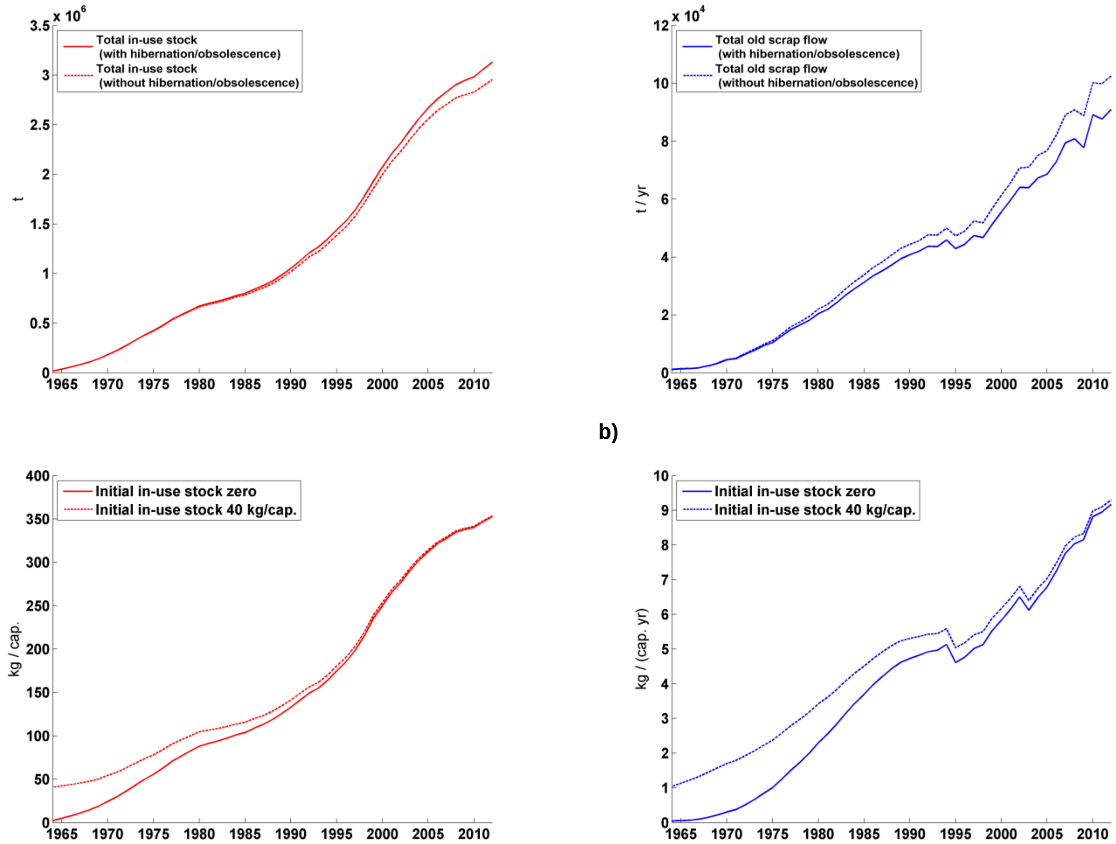
Figure S6 uncertainty effect on model outputs is shown. For the total stock a deviation of about 5% is observed, the effect on total old scrap generation is slightly higher (about 7%).

Effects of initial stock assumptions:

In contrast to hibernation and obsolescence effects, which cause some variation in model outputs at the very end of the modelling period, initial stock assumptions are most influential at beginning of the modelling period. Since hardly any data on production and trade before 1964 is available, linear inputs are assumed between 1944 and 1964. Starting with a total input of 10,000 t in 1944 with an annual increase of 1,000 t, yields a total stock of 40 kg/cap. in 1964 by using the identical parameters (sector split ratios, average lifetimes) as in 1964. In Figure S6c-d the effect of an initial stock assumption of 40 kg/cap. in 1964 on the total in-use stock and the total old scrap generation in the modelling period is shown. Clearly the effect of initial stock assumptions is most influential for the first 20 year of the modelling period. But in 1990 the difference already decreases to 11% for total old scrap generation and 6% for total in-use stock. At the end of the modelling period (2012) the difference for total old scrap generation is around 1% and for total in-use stock <1%. This clearly shows that current old scrap generation and in-use stocks are hardly affected by initial stock assumption in 1964.

Table S10. Sector specific rates of not discarded Al from in-use phase

Transport	5%
Building and Infrastructure	15%
Mechanical Eng.	15%
Electrical Eng.	30%
Consumer	5%
Packaging	0%

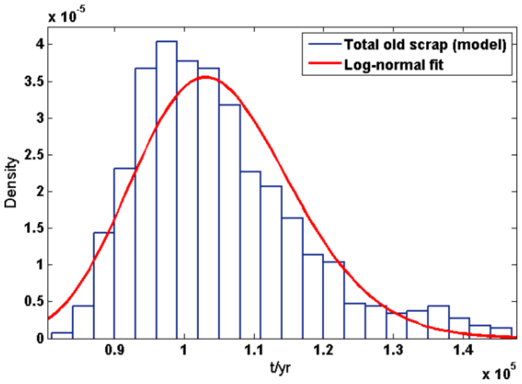


a) b) c) d)

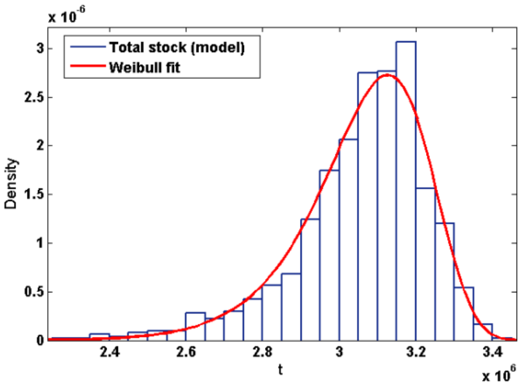
Figure S6. Effects of hibernating and obsolescence as well as initial in-use stock assumptions on in-use stocks and total old scrap generation

9. Statistical analysis of model outputs

Considering on model main model outputs in Sec. 3.2 of this work shows that output values are not normally distributed. In Figure S7 Monte Carlo outputs for the total stock and total old scrap generation are plotted as histograms for the model year 2012. Values of total old scrap right-skewed (Figure S7a) whereas values of total stock are left-skewed (Figure S7b). Even though various distributions are convoluted during model calculation, values of the total stock still fit quite well to the shape of a Weibull distribution, while old scrap values follow a lognormal distribution. Medians and interquartile ranges between the 2.5% and 97.5% quartile are given in Table S11.



a)



b)

Figure S7. Histograms and fitted distributions of main model outputs

Table S11. Median and interquartile range for a 95% confidence interval

	Total old scrap [t/yr.]	Total stock [t]
Median	1,0x10^{5}	2.9x10^{6}
Interquartile range	[0.8-1.35]x10^{5}	[2.4-3.2]x10^{6}

10. Global sensitivity analysis (EASI algorithm)

Global sensitivity analysis:

In general sensitivity analysis aims at analysing the effect of the uncertainty of model inputs on the model output. In this study a variance-based approach is used for evaluating the effects of key parameters (tc_{sec} , average lifetimes, Al concentration in final goods) on total old scrap generation. Variance-based approach means, that the total variance of the output is split up into fractions originating from each of the uncertain input parameters. The relative share of one input on the total variance is interpreted as a direct measure of sensitivity. For this purpose, first order effects (first order indices are distinguished (discussed in more detail in the materials and methods section of the main document) from higher order effects (higher order indices). While first order indices only reflect the direct influence of one parameter on the model output, higher order indices reflect the sensitivity of the model output with respect to the interaction between uncertain parameters. However , an evaluation of higher order effects requires very high computational efforts since series of first order and higher order effects in accordance with Eq. S2 have to be calculated, which results in as many as 2k-1 combinations for a given number k of parameters (Saltelli et al. , 2008). In the dynamic Al flow model 4095 combinations would be necessary in order to recover 100% of the variance. Therefore, in this study only the importance of first order sensitivities for the model results is analysed. Apart from ignoring interaction effects in the present analysis, the relationships between the time-dependent model inputs and parameters with the model outputs at later years poses a major challenge for the interpretation of the calculated sensitivity indices. This is an issue particularly for the later years of the model period. In the future, global sensitivity analyses should be extended to understand the interaction between parameters in a more mechanistic way and to identify feasible approaches of including the time dimension in such sensitivity analysis.

$$\sum_{\mathrm{i}} \mathrm{S_i} + \sum_{\mathrm{i}} \sum_{\mathrm{j>i}} \mathrm{S_{ij}} + \sum_{\mathrm{i}} \sum_{\mathrm{j>i}} \sum_{\mathrm{l>j}} \mathrm{S_{ijl}} + \cdots + \mathrm{S_{123 \ldots k}} = 1 \qquad \text{(S2)}$$

EASI:

Sensitivities addressing parameter uncertainties are evaluated through an algorithm named EASI (Plischke, 2010) that estimates first order sensitivity indices from given data. EASI conducts a variance based global sensitivity analysis using a frequency-based Fast Fourier Transformation. Signals of know frequencies are assigned to the input parameters within the calculation of first order indices subsequently the influence of each input parameter is evaluated through a frequency analysis of the output. For calculation of the sensitivities in this study values of each parameter (tc_{sec} , average lifetimes, Al concentration in final goods) derived from MCS for every year are passed to the EASI function together with the total old scrap of the given year. This finally leads to an evaluation of sensitivity for every parameter in every year (cf. Figure 5). Problematic aspects of applying this algorithm regarding the consideration of time as an external parameter and regarding the convolution of functions within dynamic MFA models are briefly discussed above and in the main document.

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Paper 3

Future raw material supply: opportunities and limits of aluminium recycling in Austria

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RESEARCH ARTICLE

Future Raw Material Supply: Opportunities and Limits of Aluminium Recycling in Austria

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Abstract In order to promote sustainable production by using secondary raw material from existing material stocks, complementary to primary raw material, information about the future availability of secondary resources constitutes a prerequisite. In this study, a dynamic material flow model of historic aluminium (Al) flows in Austria is combined with forecasts on future Al consumption to estimate the development of old scrap generation and in-use stocks until 2050. In-use stocks are estimated to increase by 60 % to 515 kg/cap. by 2050 assuming a scenario of moderate economic growth. Old scrap generation in 2050 would thereby more than double (up to 30 kg/cap.) in comparison to the 2010 amounts. Despite this substantial increase in old scrap generation, industrial self-supply from old scrap will probably not exceed 20 %, and final consumption self-supply of Al will not exceed 40 % given present conditions. Opportunities and limits of increasing self-supply through higher collection rates and lower scrap export levels are investigated in this study as the European Raw Material Initiative considers enhanced recycling to be a key measure to ensure future resource supply. Based on these analyses, a self-sustaining Al supply from post-consumer Al is not expected if current trends of Al usage continue. Therefore, comprehensive resource policy should be based on a profound understanding of the availability of primary and secondary resources potentials and their dynamics.

Keywords Future aluminium scrap · Recycling · Secondary raw material supply · Dynamic material flow modelling

Introduction

The latest economic crisis underlined that industry is an important pillar of the European economy. In order to strengthen the European economy, the European Commission aims to raise the share of manufacturing back to 20 % of GDP by 2020 [1]. The supply of industry with raw materials has been identified as one of the major weaknesses hampering the growth of industry [2]. Therefore, several raw material initiatives [3, 4] have been launched in order to secure raw material availability. The EU strategies focus on three core aspects: (1) access to raw materials on global markets, (2) sustainable extraction of primary raw materials in the EU and (3) increasing recycling and resource efficiency as well as substitution of critical materials in order to ease the dependence on primary raw material imports [5]. Even though aluminium (Al) is not on the list of materials facing a critical shortage, the material amount provided from mining production within the EU is below 10 % of global supply [6]. Due to high energy costs and strict environmental regulations, Europe is facing a decreasing trend in primary production, reaching a level below two million tonnes in 2013 [7], corresponding to 14 % of total European Al supply. Despite economic

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disruptions between 2008 and 2010, secondary production has been increasing since the 1980's, with a level of 35 % of total European supply in 2012. However, 51 % of European Al supply is still covered by imports [8]. For countries without primary production (e.g. Austria), these trends could be even more pronounced. After the close-down of primary production in 1992, secondary production nearly sextupled between 1992 and 2012. The share of imports in total scrap inputs (excl. dross and internal scrap) of Austrian smelters is at a level of nearly 80 %. This highlights that even though Al is not a critical material in terms of global availability, continuous availability is crucial for maintaining the smelter industry and for the prosperous development of the economically important downstream industries. Hence, an evaluation of the possibilities and limits of increased recycling is important in understanding the potential for the domestic supply of secondary raw materials. This is illustrated for Austria by addressing the question of how future availability of national scrap resources could contribute to satisfying national Al demand. Therefore, a dynamic material flow model (dMFM) of anthropogenic Al stocks and flows [9] is extended to predict (potential) future Al recycling potentials. Building on the historical model, which delivers a timely discretized pattern of the current in-use stocks, a forecast of old scrap flows as well as in-use stock until 2050 is performed based on scenarios about future consumption trends and stock developments for various in-use sectors. By analysing the future trends in potential old scrap generation and in-use stock development, three major questions are tackled within this study: (1) how will the in-use stock and old scrap generation develop with respect to the major in-use sectors and different scenarios of future Al consumption? (2) What implications of future national self-supply can be expected from predicted scrap amounts, both from a final consumption (= consumption at in-use) and an industry perspective? (3) To which extent are the results' uncertainties caused by parameter uncertainties in the historical model in contrast to uncertainties associated with scenario assumptions on future trends of Al production and consumption?

Materials and Methods

Model Definition

In a previous work [9], a dMFM of historical Al flows in Austria was developed. In this model, a plurality of data (e.g. historical production and trade data, material efficiencies, sector split ratios and average lifetimes) are considered in order to calculate annual in-use inputs, in-use stocks and old scrap generation with respect to the six major Al-use sectors: Transport, Buildings and Infrastructure, Mechanical Engineering, Electrical Engineering, Consumer products, and Packaging. Through tracing the development of in-use stocks and old scrap flows, the total amount of Al in-use in 2012 is calculated (360 kg/cap.). Since most in-use sectors (except Packaging, where a stock is only built up for reusable packaging material) exhibit long average lifetimes, ranging from 10 years (Consumer products) up to 40 years (Buildings and Infrastructure), existing in-use stocks will have a strong influence on future old scrap generation.

However, in order to forecast development of in-use stocks and old scrap generation, the future final consumption of Al has to be considered as well. Therefore, the existing model of historical Al flows (Fig. 1 (left)) is combined with forecasts on future final Al consumption, and a forecast model of Al stocks and flows until 2050 based thereon is developed (Fig. 1 (right)). Future inputs are calculated individually for each sector either using a stock-driven or an input-driven approach (cf. Table 1).

Future Consumption Scenarios

Based on the calculated in-use inputs and in-use stocks (in 2012) of the historical model, future trends are extrapolated. Therefore, a stock-driven method [10, 11] is used for the sectors Transport, Building and Infrastructure and Electrical Engineering. For the Transport sector the growth of population, the level of motorization and the average Al content of new vehicles represent the key parameters of the model. The prediction of the future demand of Al in buildings is based on forecast data of the Austrian Conference on Spatial Planning concerning the future development of in-use stocks in residential buildings [12]. Since forecast data on non-residential buildings (commercial and infrastructure buildings) are not available, the non-residential building stock is assumed to grow at the same rate as the residential sector. For the Electrical Eng. sector, the growth rates of in-use stock are calculated based on the network development plan of the Austrian transmission system [13]. In order to account for different intensities of Al use for each sector, a base scenario (Middle Scenario), a scenario of high Al intensity (High Scenario) and a scenario of low Al intensity (Low Scenario) are defined. Middle, High and Low scenarios for stock-driven sectors are calculated through variation of the average Al content in new cars for the Transport sector, through different Al intensities in kg/m^2 for the Buildings and Infrastructure sector and through variation of system expansion in the power grid network for the Electrical Eng. sector. A detailed description of calculations of in-use stock development in the Transport as well as the Buildings and Electrical Eng. sectors is given in the Online Resources (OR).

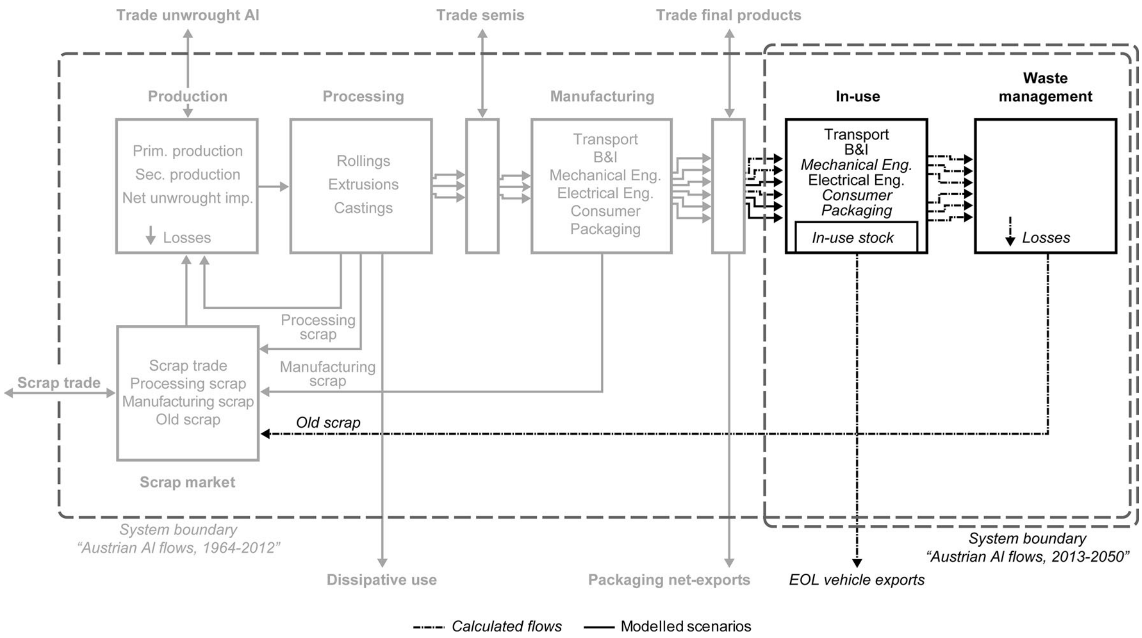

Fig. 1 System definition of the national Al flow system. Historical and future models are indicated through different system boundaries

Table 1 Scenarios of sector-specific future Al final consumption differentiated by modelling method and Al intensity

Sector	Method	CAGR and relative increases[b] [2030, 2050] in %		
		Low	Middle	High
Transport	Stock-driven[a]	1.84 [56, 100]	2.29 [77, 137]	1.22 [32, 58]
Buildings and Infrastructure	Stock-driven[a]	1.34 [41, 66]	1.53 [49, 78]	2.31 [82, 138]
Mechanical Eng.	Input-driven	1.29 [25, 63]	1.86 [38, 101]	2.32 [50, 139]
Electrical Eng.	Stock-driven[a]	1.44 [72, 72]	1.85 [87, 101]	2.25 [103, 133]
Consumer	Input-driven	0.70 [13, 30]	1.25 [24, 60]	1.70 [34, 90]
Packaging	Input-driven	0.49 [9, 21]	1.39 [27, 69]	2.06 [46, 117]

Annual increase of final Al demand expressed by compound annual growth rates (CAGR) and increase of final Al demand expressed as relative increase by 2030 and 2050 compared to the final Al demand of the Middle scenario in 2012

[a] CAGRs of final Al consumption have been recalculated from the stock modelling approach and are shown here for comparative purposes. Detailed data are used for model calculation (see Sect. 1 of the OR)

[b] Final Al demand of the middle scenario in 2013 is taken as the basis of comparison for each sector

For the remaining in-use sectors (Mechanical Eng., Consumer and Packaging), where available data are insufficient for a stock-driven approach, an input-driven approach is used. Thereby sector-specific forecasts on future Al final consumption in Europe are utilized [14]. The forecasts of Al final consumption in 2050 are therefore recalculated to annual growth rates given in Table 1. The Middle scenario complies with the estimates provided by the EAA. For the High and Low scenario, the final consumption in 2050 is increased and decreased by 30 %, and the annual growth rates are adjusted accordingly. Regarding both approaches (stock-driven and input-driven), the applied High and Low scenarios are not intended to reflect extreme scenarios of Al use. They are intended to provide some variation of the base case (Middle scenario), especially in terms of uncertainty evaluation (cf. "Evaluation of Uncertainty" section). Since dMFM is more suitable for estimating long-term trends than estimating stock and flow values for certain years [9], the initial input values (year 2012) for the modelling of future flows are derived by a linear fit of historical inputs (see Chap. 2 of the OR). Years given in graphs and tables correspond to the particular calendar years.

Defining Raw Material Self-supply

A consistent definition and application of recycling indicators are a prerequisite for comparing efficiency of material use in different countries and systems [15, 16]. According to the definition of the European Metals Association (Eurometaux), the End-of-Life recycling rate (EoL RR) is the main indicator for evaluating the efficiency of turning available old scrap into actual recycled old scrap [17]. EoL RR consists of the End-of-Life collection rate (EoL CR) and the End-of-Life processing rate (EoL PR). While the EoL RR provides information on the efficiency of the system regarding old scrap collection and processing, the recycled content is the share of old scrap in the material used for semis production [16], and thus is an indicator of raw material self-supply. Since unwrought Al trade flows could not be further distinguished as Al used for semis processing and Al used in production, in this study, the self-supply of Al is defined as the (potential) share of old scrap in national secondary Al production ($ss_{sec.prod}$) and national final consumption ($ss_{consumption}$), respectively [cf. to Eqs. (1) and (2)].

$$ss_{sec.prod} = \frac{\text{Total old scrap}}{\text{Sec.production}} \tag{1}$$

$$ss_{consumption} = \frac{\text{Total old scrap}}{\text{Nat.consumption}}, \tag{2}$$

where $ss_{consumption}$ is calculated for the Middle scenario of final Al consumption; for the calculation of $ss_{sec.prod}$, two different trends (2 and 4 % CAGR) for national secondary Al production are assumed. In order to display the opportunities and limits of enhanced recycling (increased recycling is proposed in the EU Raw Materials Initiative), the old scrap collection rate in the model is stepwise increased (within 20 years) to a theoretical value of 90 % for all sectors where current collection rates are below this value (recycling scenario R_{high}). Moreover, the potential for enhancing national Al recycling was investigated by assuming the termination of end-of-life vehicle exports (recycling scenario R_{max}). In addition to collection losses, losses during processing [18] and melting [19, 20] are considered when calculating the rate of self-supply (Table 2).

Evaluation of Uncertainty

In the historical model, an uncertainty analysis regarding key parameters (sector split ratios, average lifetimes, and average Al content in final goods) has been conducted using Monte Carlo Simulations (MCS), in order to determine potential variability of final Al demand for every in-use sector. Thereby, the effect of parameter uncertainty on current stocks and flows of Al is considered. Detailed information on chosen mean values and parameter distributions is given in "Conclusions" section of the OR. Since inputs of the forecasting model do not further depend on sector split ratios and Al content in final goods produced in the past, since future stocks and flows have been based on the estimated stock and flows in 2012, the average lifetime is the only remaining uncertain parameter in the forecast model. Other information of limited certainty or assumptions (e.g. future Al content of passenger cars, number of cars) are accounted for via scenario analysis (Middle, High and Low scenario). These scenario uncertainties originate from the indeterminacy of future Al use. Average lifetimes and uncertainties of lifetime in the forecast model are fixed to the 2012 values. The average lifetimes are 16 years for Transport, 40 years for Building and Infrastructure, 17 years for Mechanical Eng., 30 years for Electrical Eng., 10 years for Consumer products and 5 years for reusable packaging material. The relative standard deviations are 20 % for the lifetime estimates of each sector. In order to compare the effect of parameter uncertainties (originating from uncertain parameter values) with the effect of scenario uncertainty (originating from choice between Middle, High and Low scenarios) on total in-use stock and total old scrap generation, the empirical cumulative distribution functions (CDFs) are compared for the years 2010, 2030 and 2050. The relation between parameter and scenario uncertainty is evaluated by analysing the slope of the function curves (the flatter the curve, the larger is the range due to parameter uncertainties) and the distance between the resulting curves of the individual scenarios (the larger the distance, the higher is the effect of scenario assumptions on the results).

Table 2 Parameters CR, PR and melting yield for recycling scenarios R_{high} and R_{max}

	CR (current) (%)	CR (scenario R_{high} and R_{max}) (%)	PR (%)	Melting yield (%)
Transport	95	95	98[a]	95[a]
Buildings and Infrastructure	95	95		
Mechanical Eng.	80	90		
Electrical Eng.	80	90		
Consumer	50	90		
Packaging	42	90		
Packaging (reuse)	80	90		

[a] Same PR and melting yield is applied to all sectors

Results and Discussion

Future Development of In-Use Stocks and Old Scrap Generation

The forecasts of total in-use stock and total old scrap generation for Austria are shown in Fig. 2a, b. Being at a level of 3.0 million tonnes (Mt) (360 kg/cap.)at the end of 2012, total in-use stock increases to 3.9 Mt (440 kg/cap.) at the end of 2030 and finally reaches 5 Mt (530 kg/cap.) at the end of 2050. At the same time, annual old scrap generation increases from 125 thousand tonnes (kt) (14 kg/cap.) in 2012 to 210 kt (24 kg/cap.) in 2030 and 290 kt (31 kg/cap.) in 2050. Both in-use stock and old scrap generation are also shown for each in-use sector in Fig. 2c, d. The most pronounced increases in old scrap generation are expected for the Transport (3.1 times by 2050 in comparison to 2010) and the Building sectors (2.5 times by 2050). The Packaging sector's scrap generation is heavily dependent on the chosen consumption scenario due to the short residence time of packaging Al. For Electrical Eng., scrap generation increases by a factor 2.5 until 2050. The plateau-shaped trend in Mechanical Eng. is mainly caused by the adjustment of input values (final Al demand) in the historical model (see SI). Therefore, it should be regarded as a poorly founded estimate; the predicted development of future scrap generation should thus be considered as an indicative trend only. Concerning the in-use stocks in single sectors, there is evidently no sign of saturation due to increasing final Al demand for the scenarios modelled, even though decreasing growth rates can be observed for some sectors (Transport, Buildings). The biggest in-use stock increase (relative to 2012) is observed for the Transport sector (2.3 times by 2050), followed by

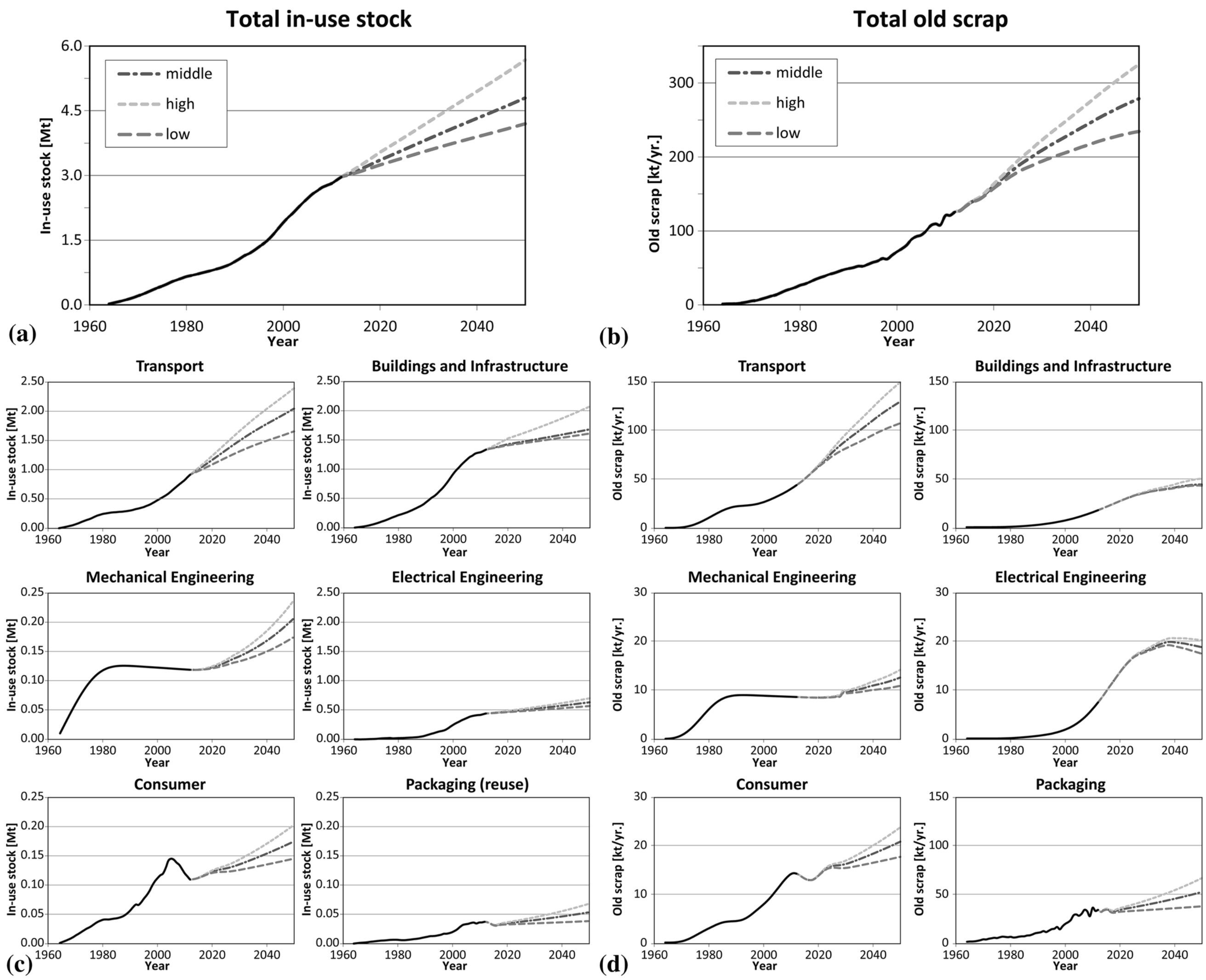

Fig. 2 In-use stocks and old scrap generation. *Different scales* are applied to the plots in sub-figure c and d, in order to highlight important and minor import sectors in terms of in-use stocks and old scrap generation

reusable packaging material (1.8 times), Mechanical Eng. (1.7 times), Consumer (1.6 times), Electrical Eng. (1.4 times) and the Building sector (1.3 times). The Transport sector is by far the dominant driver of in-use stock growth, not just in relative but also in absolute terms. The growth rates of in-use stock of reusable packaging material, Mechanical Eng. and Consumer products are driven by the assumptions on increasing future consumption.

Future in-use stock saturation levels of 400 kg/cap. have been estimated for several European countries based on historical dMFM [21], which is in line with results in this study. However, the estimated saturation level on the European average of about 200 kg/cap. [22] is much lower than the anticipated developments of Al in-use stocks in Austria suggest. Since previous studies indicate that Austria has historically been a country of high Al consumption [9, 23], in-use stock levels above the European average seem plausible.

The increase in old scrap generation (2.3 times by 2050) is more pronounced than the increase in total in-use stock (1.7 times by 2050), which indicates, on the one hand, that an increasing amount of metal may be released from current (anthropogenic) in-use stocks and, on the other hand, that average growth in final consumption is expected to fall below historical values.

Potential of Raw Material Self-supply

Self-supply with Al old scrap in Austria is calculated with respect to the industrial Al demand (secondary Al production) and the final Al consumption. The latter is used to simulate the theoretical situation, where national Al demand (final goods) has to be covered by national secondary production, considering all foreign trade flows to be zero. Assuming a 2 % CAGR for national secondary Al production, $ss_{sec.prod}$ will remain quite constant at around 18 %, with a slightly decreasing trend after 2030 (cf. Fig. 3a). If secondary production grows at 4 % CAGR, $ss_{sec.prod}$ will continuously fall to a level below 10 % by 2050. In view of the consumption, a $ss_{consumption}$ around 40 % of the consumption could be satisfied through domestic old scrap in the case of the Middle scenario (cf. Fig. 3b). Analysing the effect of enhanced recycling on self-supply with old scrap indicates that for the recycling scenario R_{high}, the national self-supply at in-use stage $ss_{consumption}$ will increase to nearly 50 %. If exported “end of life” vehicles are additionally accounted for, national recycling $ss_{consumption}$ may increase up to 74 % by 2050. However, from the production perspective, only a 3 % increase of $ss_{sec.prod}$ can be achieved by enhanced recycling given a 4 % CAGR. If in addition vehicle exports are terminated, a 6 % increase of $ss_{sec.prod}$ could be achieved.

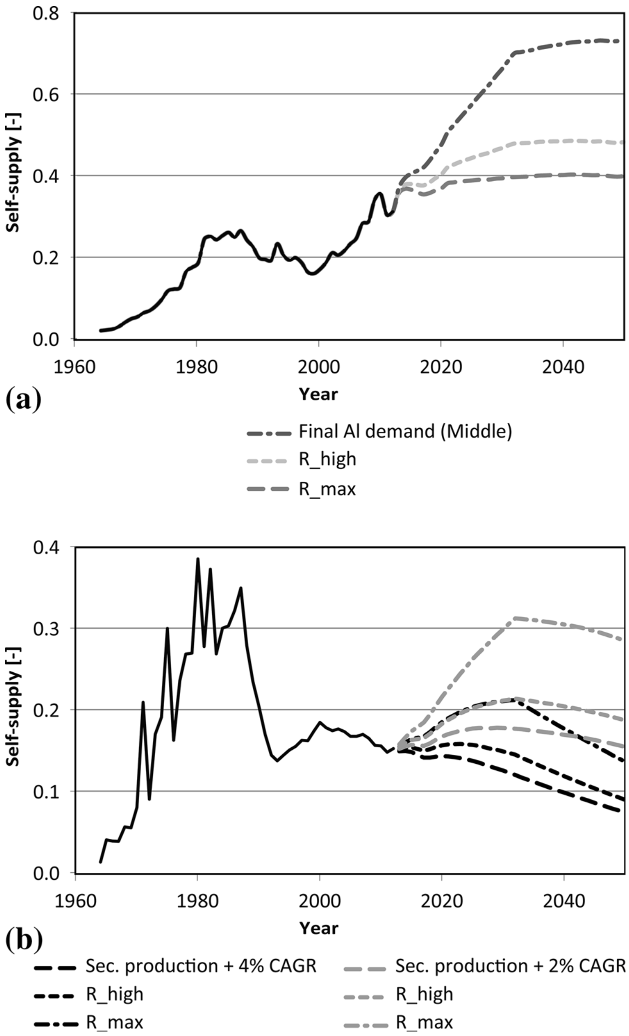

Fig. 3 **a** Self-supply regarding future old scrap generation and secondary production ($ss_{sec.prod}$) and **b** self-supply regarding future old scrap generation and in-use consumption ($ss_{consumption}$). Recycling scenarios R_{high} and R_{max} are indicated in *dashed lines*

In the case of assuming a 2 % CAGR for secondary production, the corresponding $ss_{sec.prod}$ would reach around 30 % by 2050, highlighting the strong effect of the growth rate chosen on the potential for production of self-supply [16]. However, in analysing the potential effects on self-supply through enhanced recycling measures, one has to keep in mind that not all vehicles exported nowadays are really scrap vehicles (e.g. used-car trade). Therefore, the effect of terminating vehicle exports on self-supply is probably overestimated in the present analysis (i.e. it is a partly unrealistic potential). Furthermore, processing scrap from the production of semi-finished products as well as manufacturing scrap is not considered in the calculation of self-supply. Processing scrap is mostly kept in a closed in-house cycle and therefore not available on the scrap market, while subsequent manufacturing scrap is mostly recycled in an open loop on the market but also regarded as new scrap. By including manufacturing scrap, a 9 % increase in industrial self-supply could be achieved currently. However, the effects of new scrap recycling in terms of resource and energy savings as well as environmental impacts certainly deviate from old scrap recycling, and therefore, new scrap should not be considered in terms of raw material substitution [18].

The trend of future self-supply regarding final Al consumption (Fig. 3b) indicates that complete self-supply by 2050 is not achievable given the growth rates assumed for Al consumption. Even in the best case scenario (high collection rates, no vehicle exports), self-supply could not surpass a level of 75 %. In order to contrast the forecasts of future Al consumption presented with the idea of decoupling [24], a scenario of constant per capita Al consumption is shown in Fig. 4. If per capita Al consumption remains constant at the level of 2012 (approx. 23 kg/cap.), the theoretical level of Al consumption self-supply could reach 83 % by 2050. In the case of constant per capita consumption, the amount of Al consumed increases by 11 % compared to 2012 due to population growth. In order to arrive at a consumption self-supply level of 100 % (i.e. final Al consumption = Al old scrap), Al per capita consumption would have to decrease by 30 % until 2050, assuming a linear decrease from current consumption levels. Such a 30 % decrease of per capita consumption would correspond to a decrease of 23 % in the total amount of Al consumed in Austria in the year 2050 compared to 2012. Trends in self-supply as well as total in-use stocks are shown in Fig. 4. Recycling (CR, PR) and production losses are not considered in the trends of self-supply (given in Fig. 4), thus resulting in a theoretical self-supply

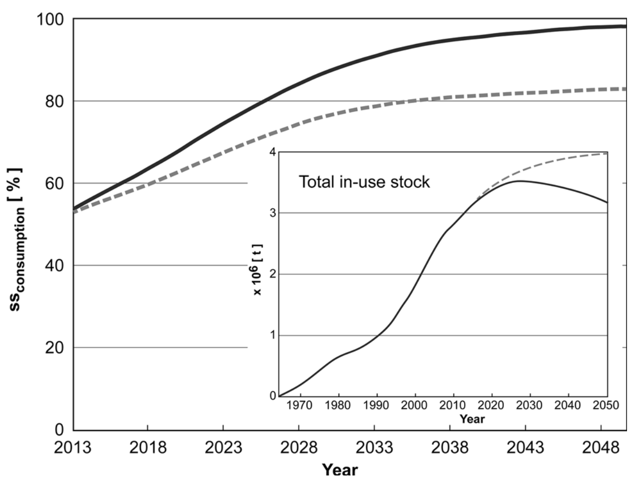

Fig. 4 Self-supply ($ss_{consumption}$) with constant per capita consumption (*dashed line*) and self-supply with a 30 % decrease in per capita consumption (*solid line*) until 2050. Corresponding total in-use stock developments are shown to the *right*

situation because 100 % recovery of end-of-life Al is not possible in a real system due to dissipative losses during usage, considerably increasing recycling efforts in order to obtain high CR and PR and thermodynamic limitations in production.

Parameter Versus Scenario Uncertainty

The effects of parameter uncertainties (historical model) and scenario uncertainties (forecast model) on total in-use stock and total old scrap generation are shown in Fig. 5 for the years 2010, 2030 and 2050. Parameter uncertainty reflects the influence of the parameter values, chosen in the historical model, on current in-use stocks, which are of major importance to determine future old scrap generation. Scenario uncertainty reflects the indeterminacy of future final Al demand, which is approximated by choosing a range of scenarios (Low, Middle and High).

In 2010, the CDFs of the scenarios are practically identical for both in-use stock and old scrap generation as the estimated consumption scenarios are not relevant. From Fig. 5a, it becomes obvious that the curves for old scrap and total stock are oppositely skewed. Values of total old scrap generation are right-skewed (point of inflexion is in the lower half of the range), while in-use stock values are left-skewed (point of inflexion is in the upper half of the range). The data intervals containing 90 % of the model results (between the 5th and the 95th percentile) are given in Table 3. In 2030, the influences of the consumption scenarios on in-use stock and scrap generation are indicated by the distance between the CDF curves of the individual scenarios. Regarding in-use stock, the Low and the Middle scenarios show very similar results, whereas the high consumption scenario exerts a more pronounced effect on the resulting in-use stock estimates. The uncertainty related to the average lifetimes in the forecast model and to the parameters of the historical model (sector split ratios, Al concentration in final goods and average lifetimes) causes nearly a doubling of the resulting uncertainty ranges (expressed via the 90 % data intervals of the MCS results). In 2050, the distances between the Low and Middle scenario CDFs for in-use stock are practically the same as between the Middle and High scenarios. However, compared to 2030, the scenario choices have a higher influence in 2050 than the uncertainties of model parameters. For the total old scrap generation, similar patterns of parameter and scenario uncertainty are observed (cf. Fig. 5). Scenario-dependence increases over time, resulting in distinct displacement of the CDF curves in 2050. In contrast to scenario uncertainty, parameter uncertainty (width of the 90 % data interval of a scenario CDF) decreases over time since after 2010 the only uncertain parameters remaining are the average sector-specific

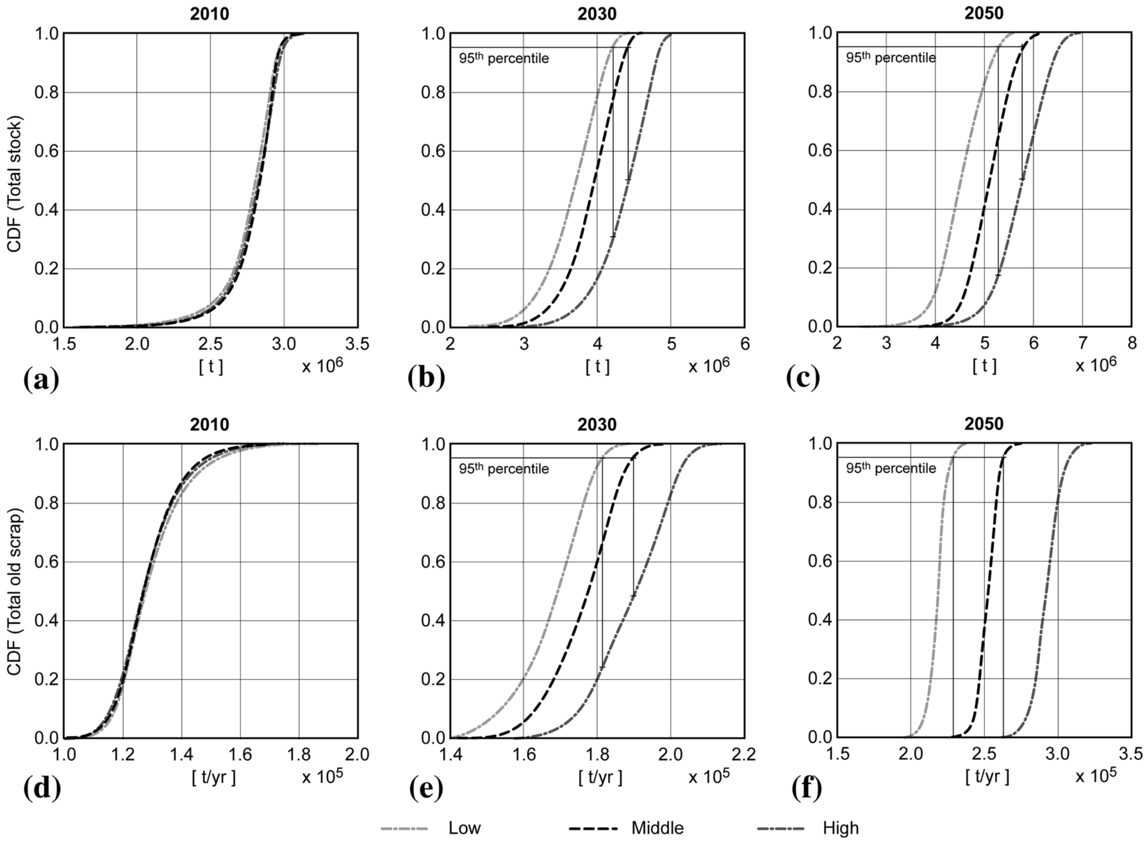

Fig. 5 CDF plots of total in-use stock and total old scrap generation for the years 2010, 2030 and 2050

Table 3 Intervals between the 5th percentile and the 95th percentile (90 % data intervals) of the Monte Carlo simulation results for total in-use stock and old scrap generation

	2010			2030			2050		
	Low	Middle	High	Low	Middle	High	Low	Middle	High
Total in-use stock [t $\times$ 10^6]	[2.4, 3.0]	[2.4, 3.0]	[2.5, 3.0]	[3.0, 4.2]	[3.2, 4.5]	[3.7, 4.9]	[3.8, 5.3]	[4.4, 5.9]	[5.0, 6.6]
Total old scrap [t $\times$ 10^5]	[1.1, 1.5]	[1.1, 1.5]	[1.1, 1.5]	[1.5, 1.8]	[1.6, 1.9]	[1.7, 2.1]	[2.1, 2.3]	[2.4, 2.5]	[2.8, 3.1]

lifetimes. Old scrap in 2050 therefore mainly depends on the choice of the consumption scenario and is hardly influenced by the uncertainty of model parameters.

The overlap of the Middle, High and Low consumption scenarios in 2030 and 2050 is indicated in Fig. 5b, c, e, f by vertical lines at the 95th percentiles of the Low and Middle scenarios. In the case of in-use stock, the 95th percentile of the Low scenario in 2030 (Fig. 5b) is higher than 75 % of the simulated values of the Middle scenario and 30 % above all values estimated for the High scenario. Thus, there is a 70 % probability that the in-use stock resulting from the High scenario lies above the 95th percentile of the in-use stock resulting from the Low scenario in 2030. For 2050, the scenario-related differences increase and, consequently, 80 % of the High scenario results lie above the 95th percentile of the Low scenario results (Fig. 5c). The probability that the in-use stock of the High scenario is above the 95th percentile of the Middle scenario' results is around 50 %. With respect to total old scrap generation, the percentile comparisons indicate a stronger dependency of the results on the scenarios. For instance, only 65 % of the Middle scenario results and 45 % of the High scenario results are below the 95th percentile of the Low scenario in 2030 (Fig. 5e). In 2050, all of the results of the Middle scenario are above the 95th percentile of the Low scenario's old scrap generation (Fig. 5f). The same holds for the comparison between the Middle and High scenario, highlighting the dominating role of the scenario choices for these results.

Discussion of Scenario Trends

According to the scenarios of future Al consumption analysed, the sectors Transport and Buildings will remain the key drivers of old scrap generation. Projected targets of increasing the Al content in cars, mainly driven by Al used for body-in-white and hang-on parts, will considerably increase the old scrap recycling potential from the transport sector [25]. Scrap generation from Buildings is dominated by the long average life times, which will make currently used Al available in future. In any case, concerning the Transport sector, it should be mentioned that the effect of a potential increase in electric cars at the expense of conventional cars is not considered in this study. An increase in the electric vehicle fleet would most likely induce a reduction of cast Al used in transport, whereas the use of wrought Al for structural parts would basically not be affected by the type of propulsion [26]. Cast Al content in future electric cars is expected around 50 kg, compared to a quite constant Al content of around 100 kg in gasoline and diesel cars [26]. Considering the expected increase of wrought Al parts in cars, which will be the main driver of Al demand in the transport sector (electric and gasoline cars), an average Al content of 190, 270 and 320 kg per vehicle is estimated in this study (cf. Chapter 1 of the OR). Consequently, taking into account an increasing share of electric cars in the vehicle fleet would indicate a propensity to the Middle and Low scenarios of this study, where a lower average Al content per car is assumed. Drastic changes in terms of future electrical car penetration are not considered, because also the BLUE map scenario of the International Energy Agency expects that the share of conventional vehicles and vehicles with conventional components (hybrid, plug-in hybrid) in total light-duty vehicle sales will still be around 65 % in 2040 [27], which indicates a continuing dominance of conventional, fuel-based technologies in vehicles. Nevertheless, increasing shares of electric cars might result in lower Al intensities and consequently in lower Al inputs to the Transport sector, than considered in the present analysis. However, it should also be noted that Al use is in competition with other light-weight materials [28]. Furthermore, there is no certainty that the same trend of increasing Al content also applies to other vehicle categories (e.g. commercial vehicles, motorbikes etc.), which is assumed in the present study. Considering the above-mentioned aspects influencing future Al use in cars, the scenario assumptions cover a plausible range of potential Al usage in cars without taking into account potential extreme developments in the Transport sector.

Similar assumptions have been made for the Building sector, where the calculated stock growth rate of residential buildings is also applied to buildings in the fields of commerce and infrastructure. Due to the currently higher Al intensity in commercial buildings, this assumption may lead to an underestimation of future stocks, but data on commercial buildings are not available for the case of Austria.

Comparing current secondary production to current final Al demand shows that final Al demand is currently in the magnitude of 50 % of secondary production. If future secondary production grows at 4 % CAGR and final Al demand at a level of 1–2 % CAGR, final Al demand will be only 20 % of secondary production in 2050. This clearly indicates that future growth of secondary production will be mainly driven by the export of products.

Based on increasing Al consumption in all in-use sectors, no saturation is observed for the in-use stocks in the model. Therefore, the present analysis provides some indication that saturation will not occur before 2050 in highly developed European economies, such as Austria. This is an important finding as the time required to reach a theoretical saturation level is a crucial assumption in stock-driven approaches to material flow modelling [21, 22].

Conclusions

As far as the raw material initiatives of the EU are concerned, it should be noted that self-supply from old scrap in Austrian secondary Al production will most likely not exceed 30 %, and even 30 % would require quite restrictive measures limiting exports of end-of-life products (e.g. cars) in combination with increased CR in national recycling, as well as growth in national secondary production at a very moderate level of 2 % CAGR. Assuming a 2 % CAGR industry and increased national recycling efforts (without limits on exports of Al containing end-of-life products), a future self-supply between 15 and 20 % may be achieved. In relation to the Al demand required to satisfy the domestic final consumption, self-supply increases over time with a theoretical maximal self-supply limit of around 70 % for the given consumption scenarios. Comparing the different trends of self-supply at the level of industrial demand and at the level of final consumption, it turns out that a more differentiated view on limits and goals of managing secondary resources is necessary. If industry objectives on annual growth are achieved, enhanced recycling exhibits quite limited power for increasing self-supply without major export restrictions. At the level of final consumption, however, increasing levels of self-supply could be expected in the future in parallel with the decelerated growth of Al in-use stocks. Nevertheless, a theoretical Al self-supply of 100 % by 2050 (losses not considered) could only be achieved through a 30 % decrease of per capita Al consumption. Thus, a self-sustaining supply to satisfy final Al demand based on domestically available secondary raw materials could only be reached through a decrease in consumption, which seems rather unlikely given historic developments. Uncertainty analyses indicate that the assumed trends in future final Al demand as well as future trends in secondary production (scenarios) have a stronger effect on the potential self-supply than model parameter uncertainties (life time of Al containing products).

Finally, it needs to be emphasized that an increasing self-supply via old scrap may result in unsuitable alloy compositions for remelting, which was not considered in the present study. Very specific and well-defined alloys are necessary in order to ensure the requirements concerning product quality. A mix of old scraps from different applications could therefore lead to undesirable levels of certain alloy elements present in the scrap, which would put a limit on the maximum amount of old scrap to be used in secondary production. However, new technologies, such as sensor-based sorting, hold some promise for at least reducing this limitation in old scrap recycling. Because lifetimes for certain in-use sectors are long, variation of alloy types used over time could also pose a challenge to high levels of self-supply. Therefore, the investigation of future Al scrap qualities based on the Al alloys used in various application sectors can shed further light on the potential for Al recycling and secondary raw material use, warranting future research efforts.

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Future Raw Material Supply: Opportunities and Limits of Aluminium Recycling in Austria

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1. Stock driven approach:

1.1. Transport sector

Three parameters (population, level of motorization and Al-content in new cars) have been selected as driving factors for future development of the Al stock in the Transport sector. Population data is based on forecasts of national statistics [1] and illustrated in Figure 1. Data on the level of motorization is derived from a large-scale study on future car mobility [2]. Historical and future Al-content in new vehicles is based on literature data [3; 4]. In order to calculate the average Al-content per car in vehicle stock, which deviates from Al-content in new vehicles, car inventory statistics, differentiating registered cars by date of registration, have been considered. The historical and projected trends of Al-content in new cars (1990-2020) are used to calculate the average Al-content of a car in the stock for the years 2013, 2011, 2005 and 2003, for which detailed statistics on car inventory are available. The average increase of Al-content is finally determined by a linear interpolation between these years' average Al-contents. Average Al-contents and increase of Al-content per in-use car are shown in Figure 2a according to the middle, high and low growth scenarios in Figure 2b. The future annual increase of Al-content per car in stock is finally derived from the slopes of the fitted lines in Figure 2a (3.1 kg/year, 4.2 kg/year and 1.9 kg/year for the middle, high and low scenario). Initial Al-content per vehicle in stock (2013) is 117 kg (cf. Figure 2a).

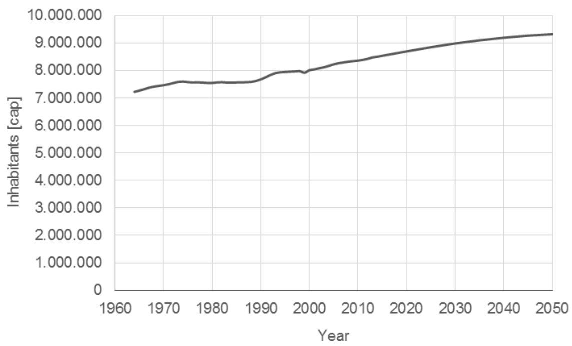
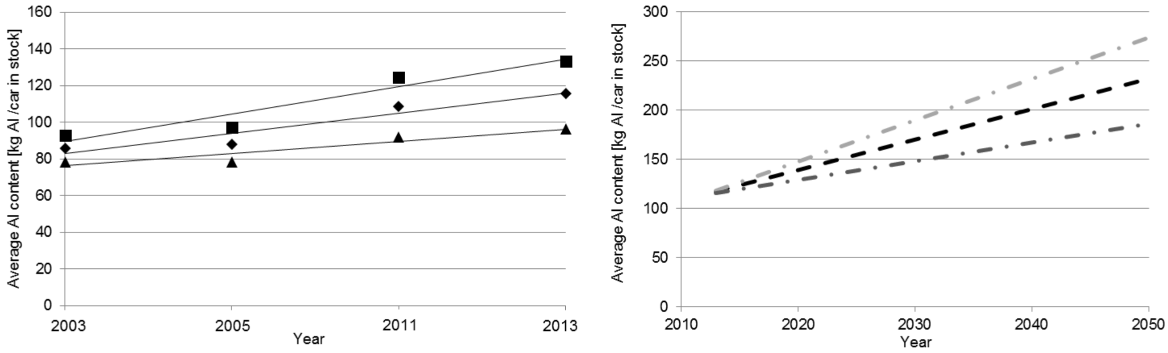
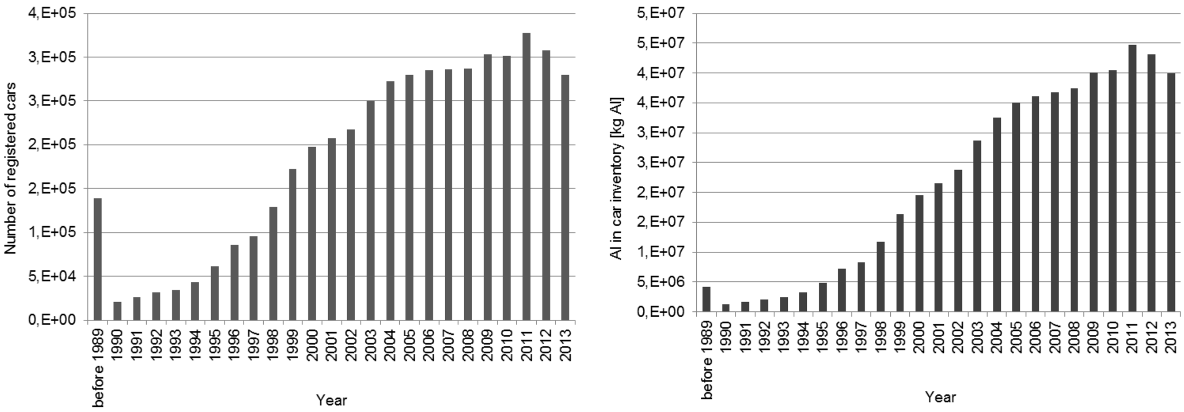


Figure 1 Historical Austrian population data and forecasts until 2050



a) b)

Figure 2 (a) Average Al-content of cars in vehicle stock for the scenarios middle, high and low Al intensity; (b) projected trends of Al-content in new cars until 2020



a) b)

Figure 3 (a) National car inventory in 2013 by date of registration; (b) Al-amount in national car inventory by date of registration according to Figure 3a and Table 1. Total number of cars 4,513,421.

The Al-content in new cars used for the calculation of the Al amount in the car fleet (Figure 3b) is based on literature values. For car registered before 1989 a Al-content of 30 kg is assumed. Since cars are the major part of the transport in-use stock [5] and estimates on future Al-content in other vehicle categories are not available, the growth rates calculated for the car stock are used for calculating future transport stock development.

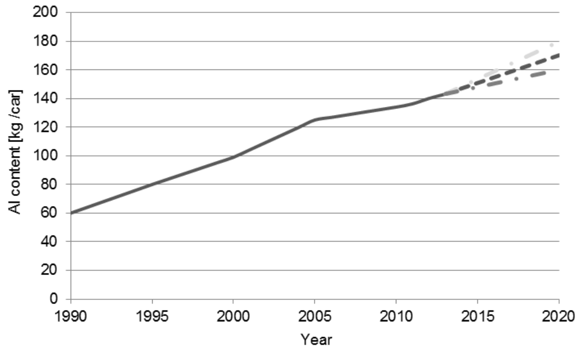


Figure 4 Evolution of average aluminium content per new car registered incl. Middle, High and Low trends of future Al content until 2020

1.2. Building sector

Estimates on the future construction activity regarding residential buildings [6; 7], form the basis for forecasting the future development of the building stock. For the period 2011-2021 an annual construction activity of 40.000 dwelling units is estimated. From 2021-2031 activity falls to 28.000 dwelling units. For the remaining modeling period, the building activity is kept constant at 28.000 units per year. The average flooring area of 93.4 square meters (2011) of a dwelling unit is available from statistics [8]. Concerning the average Al content in buildings hardly any information is available. Values reported in literature range from 0.5 kg/m^2 to 4.0 kg/m^2 [9-11]. While values below 1 kg/m^2 are mostly found for residential buildings, Al intensities above 1 kg/m^2 are typically observed for industrial, commercial and office buildings. For this study an average Al content of 0.9 kg/m^2 is assumed to calculate the Al stock in buildings. Considering a share of 30% of total Al in buildings stored in residential buildings [5] and the annual amounts of Al required for projected new dwelling units, annual growth rates of Al in buildings in-use stock until 2050 are calculated. The different scenarios (Middle, High and Low) are reflected via various Al intensities of 0.9 kg/m^2, 1.8 kg/m^2 and 0.7 kg/m^2.

1.3. Electrical Eng. sector

Calculation of the growth rates in the electrical engineering sector is based on inventory statistics of the national power grid network [12] and the network development plan of the Austrian transmission grid operator [13]. An estimation of the future stock increase based on the power grid network development is an applicable assumption, since the power grid network is considered as the main carrier of Al in this sector and inventory data on other electrical engineering applications are not available. In order to calculate the annual increase of the Electrical Eng. stock, the amount of Al stored in the 220/380kV voltage level of the power grid network in 2013 is calculated. A system length of 6.505 km [12] multiplied with an average Al content per km of 7.68 t/km results in a total Al amount stored in the 220/380kV network of approx. 50.000 t. From the development plan [13] approx. 600 km of new lines (including changeovers) until 2023 are expected. Annual growth rates are calculated from the ratio of in-use stocks and future stock increase (cf. Table 1).

2. Input-driven approach

For sectors (Mech. Eng, Consumer and Packaging) where the input-driven approach has been used to model future consumption scenarios the input values of 2012 are recalculated through linear interpolation, exemplified for the non-reusable packaging material input in Figure 5. Since input quantities in input-driven dynamic material flow models could fluctuate considerably over time, averaged values are preferable, to avoid the risk of starting at very low or very high input quantities for the future input calculation due to annual fluctuations. Since trade data in the Mechanical Eng. Sector is contradicting with calibrated sector split ratios from the historical model, the in-use input of this sector is averaged over time. The results for this (small, in terms of Al use) sector should therefore be considered as rather speculative, especially regarding the trend of old scrap generation.

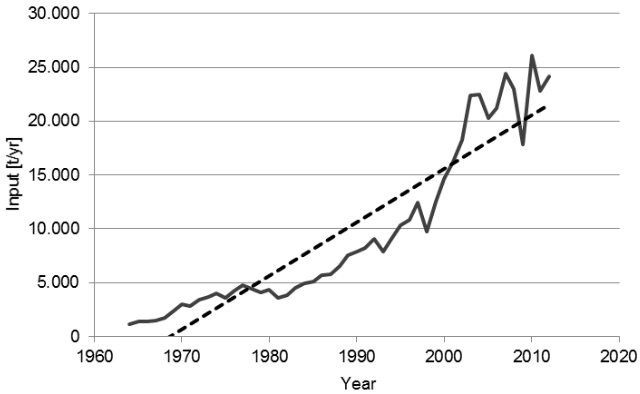


Figure 5 Linear fit of annual input quantities in order to derive averaged values for 2012 as initial value for the modelling of future inputs (exemplified for the input of non-reusable packaging material)

3. Final Al demand

Al consumption in final products is shown for the historical model and the Middle scenario in Figure 6. Currently, but also regarding the prospects of future Al use, the Transport sector is the dominating Al application. The Al consumption of other sectors is lower and also growing more moderately. If projected scenarios on Al use in vehicles are realised, the share of Al used for transport application may rise up to 50% of total final Al consumption. Fluctuation of inputs between 2012 and 2013 should rather be considered as model artefacts than real changes in inputs, due to the switch from a fully input driven historical model to an input and stock driven model based on different growth scenarios.

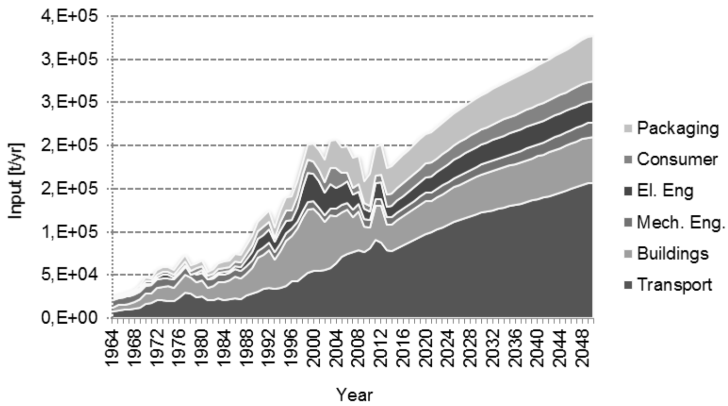


Figure 6 Historical and forecasted development of national final Al demand

4. Model parameters

In the historical (input-driven) part of the model typical parameters like sector split ratios, average lifetimes, and Al concentration in final goods are used in order to calculate annual final Al demand for every in-use sector. In total 13 parameters are varied in a Monte Carlo Simulation (1000 runs) for determining the uncertainty of the model results (historical model) due to uncertain model parameters. Normal distributions given by mean values and standard deviations are assumed for Al concentration in final goods and for the sector split ratios. In-use lifetimes are described by Weibull functions. Data from the literature are used to define the mean values and the uncertainty ranges of the parameters. An overview on parameter values and associated uncertainty ranges are given in Figures 6-7 and Table 1. For detailed information, particularly regarding mean values of Al concentration in final goods, it is referred to the original study [14].

Figure 7 Values of the sector split ratios

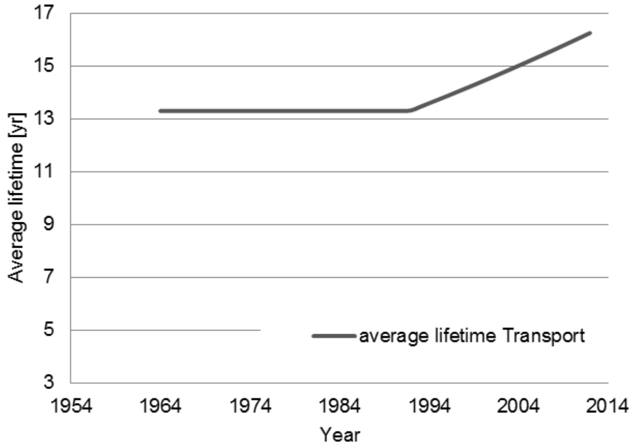


Figure 8 Time dependent average lifetime for the Transport sector (constant after 2014)

Table 1 Values and uncertainty ranges (given as relative standard deviations) used for uncertainty analysis

	Al concentration final goods	Ratio Transport	Ratio Building& Infrastructure	Ratio Mechanical Eng.	Ratio Electrical Eng.	Ratio Consumer	Ratio Packaging	Lifetime Transport	Lifetime Building& Infrastructure	Lifetime Mechanical Eng.	Lifetime Electrical Eng.	Lifetime Consumer	Lifetime Packaging (re-use)
Value	[14]	Figure 7	Figure 7	Figure 7	Figure 7	Figure 7	Figure 7	-	-	-	-	-	-
Standard deviation (relative)	30%	20%	20%	20%	20%	20%	20%	10%	30%	20%	20%	15%	10%
Scale parameter (Weibull)	-	-	-	-	-	-	-	Figure 8	40	17	25	10	3
Shape parameter (Weibull)	-	-	-	-	-	-	-	3	3	3	3	3	3

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