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]	(Comtrade,	90	(own estimate)

		69979[3]	2014)		

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	723[2-3]	5	(Recalde et al. ,

parts thereof			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).

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

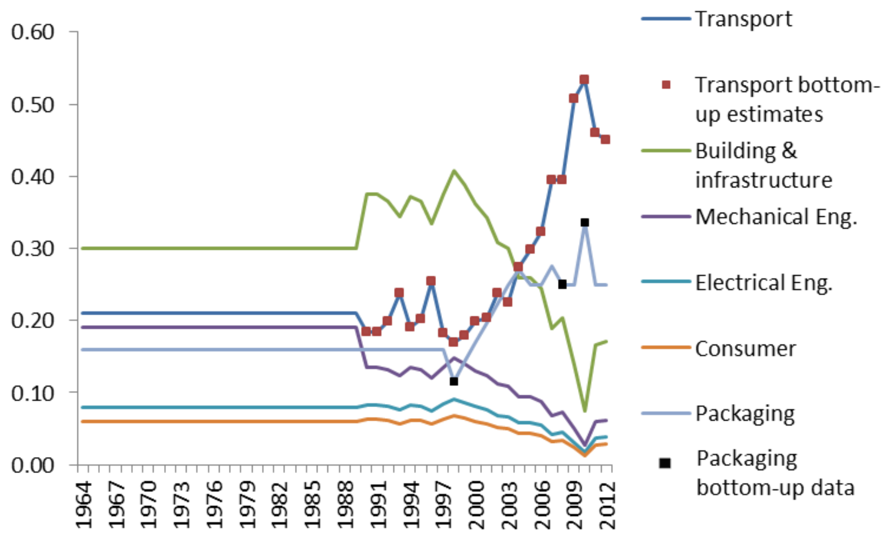
Table S4. Values and uncertainty ranges for uncertainty calculation

	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

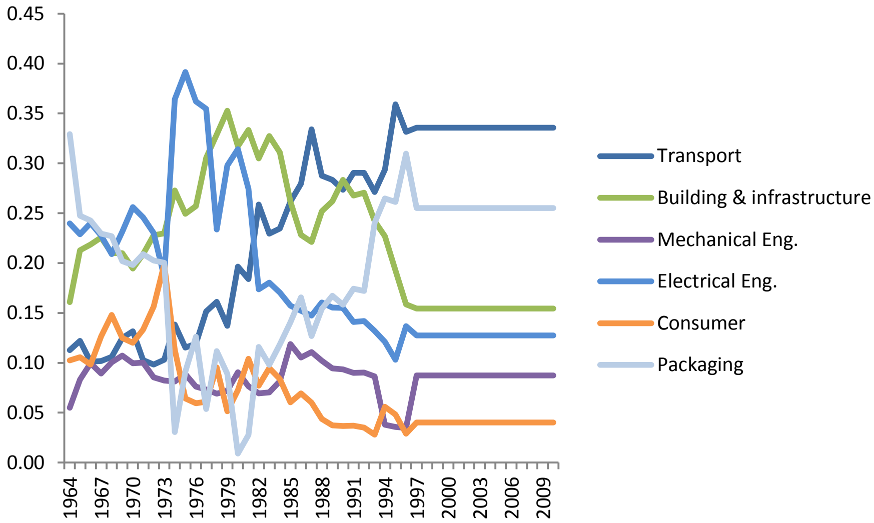
Calibration of sector split ratios

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).

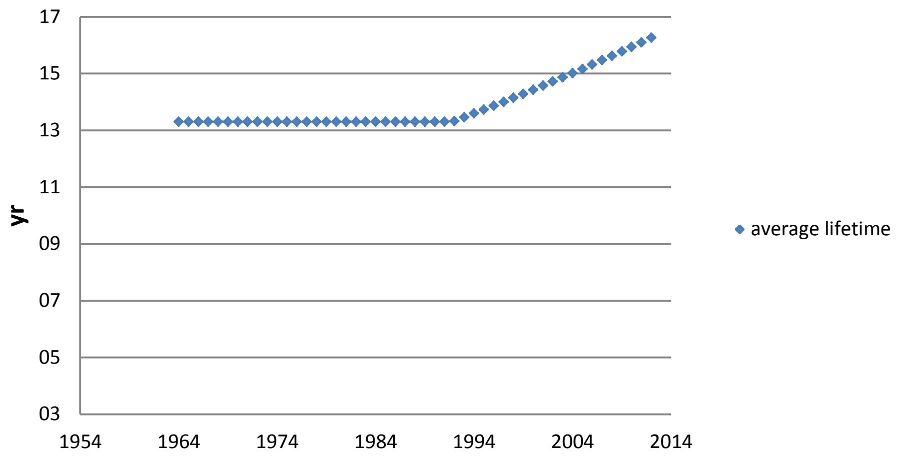


Figure S2. Time dependent avg. lifetime for the transport sector

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.

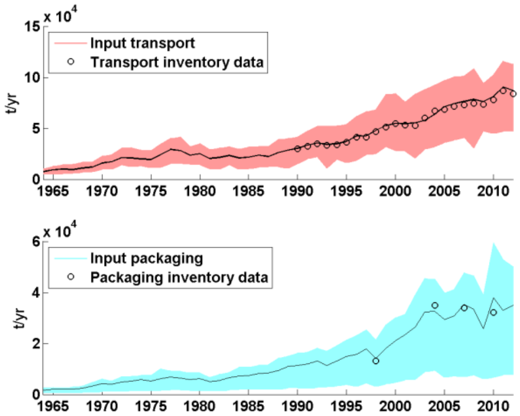


Figure S3. Calibrated Al inputs into in-use for transport (top) and packaging application (bottom). Bottom–up data for individual years is indicated (loops).

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% .

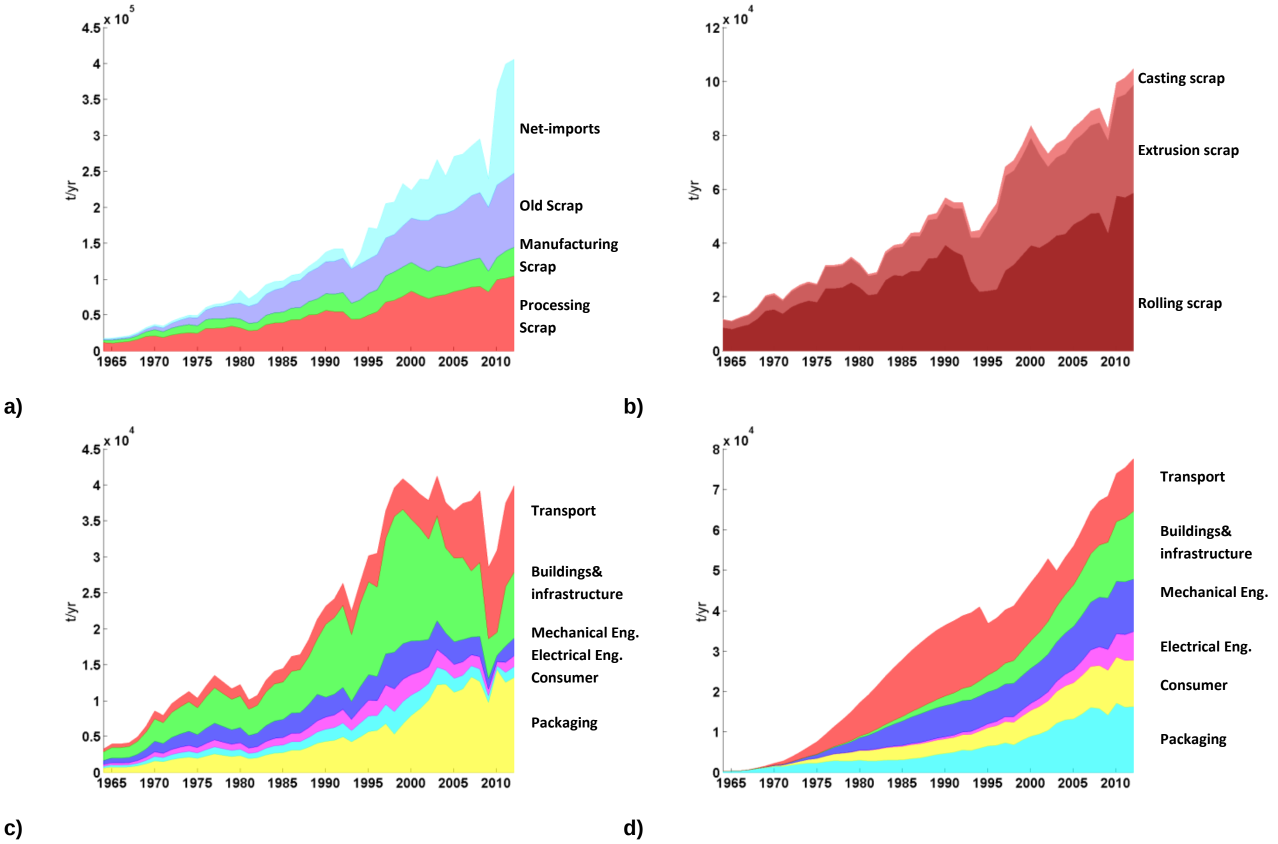


Figure S4. Generated total, new and recyclable old scrap amounts over time. a) Total Austrian scrap generation + net-imports; b) Processing scrap generation; c) Manufacturing scrap generation with respect to in-use sectors; d) Old scrap generation excl. vehicle-exports

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).

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

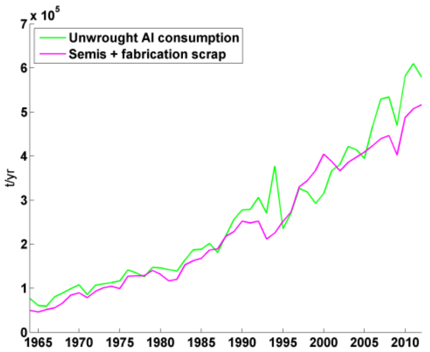


Figure S5. Unwrought metal consumption vs. semis production + processing scrap

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%

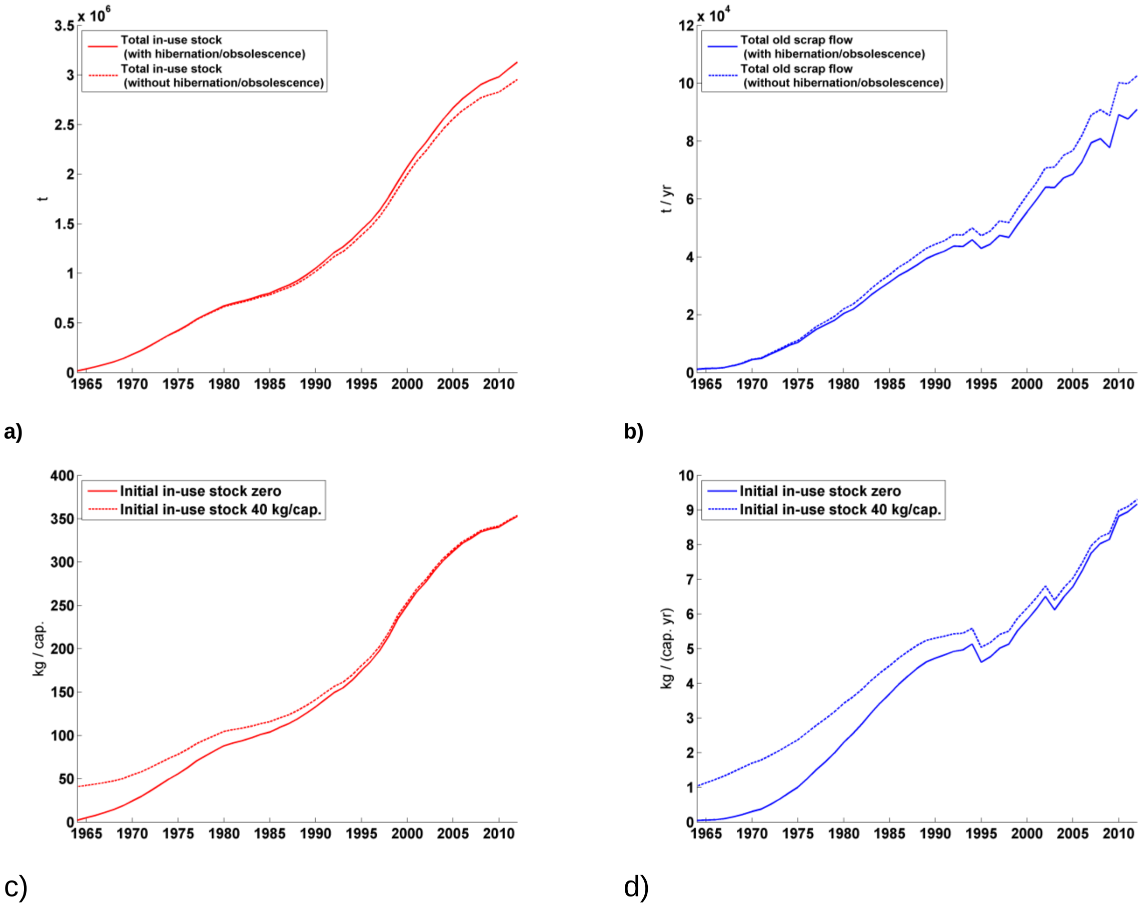
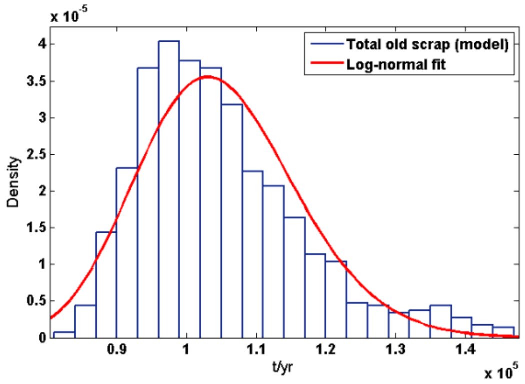


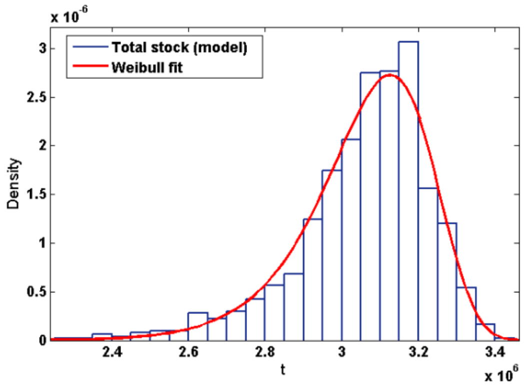
Figure S6. Effects of hibernating and obsolescence as well as initial in-use stock assumptions on in-use stocks and total old scrap generation

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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