# Tracing material use to final products in dynamic material flow analysis: a comparative application of methods to the USA and EXIOBASE regions (part II)

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# Abstract (long for now)

Several widely-cited dynamic Material Flow Analysis (dMFA) studies that investigate economy-wide material consumption extrapolate fragmented information on material end-use products, i.e. the product stocks as which materials accumulate, for single countries and years across longer time periods and global countries. However, information on material consumption in end-use prodcuts is crucial to adequately respresent product lifetimes and material service contributions to human well-being. Therefore, improving the tempo-spatial and material coverage as well as resolution of material end-use products for these ‘top-down’ dMFA techniques is important to provide robust assessment of the contributions of material consumption to well-being.

In part I of this work we reviewed and systematized five distinct approaches to derive end-use products, relying on industry shipment data in physical units and monetary input-output tables (MIOTs). Here, we empirically apply these approaches to the case study USA using national-level data. Additionally, we propose methodological improvements for a closer match of MIOT-dMFA system boundaries (‘Hypothetical Transfer’), apply these to the Multi-Regional Input-Output Model EXIOBASE, and compare results with additional industry shipments to evaluate robustness for international data sources.

We find mixed results regarding the fit of end-use shares derived from data in physical versus monetary units. For U.S. national data, some materials show rather good fit (e.g. aluminum with a relative median deviation X%), while others deviate stronlg (iron & steel --- Y%). However, in many cases the temporal trajectory of MIOT-based end-use shares approximated that of physical data, if also at different magnitude. Hopes of achieving high end-use product resolution with detailed MIOTs remain inconclusive due to little availability of physical data at that resolution. HT-WIO best results for packaging as ‘intermediate product’….For EXIOBASE

Good fit for some countries and materials (e.g. steel in China), bad for others (e.g. construction in UK).

For X compared countries very large overestimation of aluminum use in machinery

Packaging sector missing which is the largest end-use sector for plastics in many countries

To apply MIOT-based end-use shares to dMFA, without any idea of physical realities seems risky. However, together with available industry shipments, MIOT-data might add additional information regarding temporal trajectory and variance between countries. Additionally, hopes are that new developments in MRIOs that are specifically build for material flows such as GLORIA might provide better suited information.

# Introduction

To evaluate system-wide effects of changing consumption patterns, we require methodologies that quantify resource use both comprehensively, i.e. the economy-wide use of multiple materials with global long-term coverage, and detailed, i.e. establishing a connection of element and material cycles to the end-use products that humans demand for their well-being (Haberl et al. 2019). Dynamic Material Flow Analysis (dMFA) is a research field that has longstanding expertise in detailed assessments of systems of production and consumption (Müller et al. 2014; Lanau et al. 2019; Fu et al. 2021), and recently also the less detailed but more comprehensive field of economy-wide Material Flow Accounting (ew-MFA) is moving in this direction (Wiedenhofer et al. 2019; Streeck et al. 2020; Plank et al. 2022).

However, dMFA models and studies are yet often either detailed or comprehensive due to the huge efforts required to achieve both at the same time. Stock-driven ‘bottom-up’ dMFA can be very detailed but require huge efforts to achieve economy-wide coverage, if at all possible due to data constaints. The ‘Resource Efficiency – Climate Change (RECC)’, for instance, represents material use in buildings and passenger vehicles with high level of detail regarding different material qualities and end-use product archetypes but still requires large efforts to achieve full system coverage (Pauliuk et al. 2020; Pauliuk and Heeren 2020). On the other side of the dMFA method spectrum is inflow-driven ‘top-down’ dMFA which utilize statistics of economy-wide material consumption. These models can cover comprehensive material use but with little detail, i.e. no distinction of product end-uses. An example is the Material Inputs, Stocks and Outputs (MISO) model, which connects economy-wide material consumption with stock-flow modelling (Wiedenhofer et al. 2019).

Although the detail of ‘bottom-up’ models is hardly achievable via the ‘top-down’ dMFA methodology, studies that introduce meso-level end-use detail to the latter exist (Streeck et al. 2022). Examples are Dahlström et al. (2004) who introduce 6-9 end-uses to economy-wide material flows for crude iron, steel and aluminum in the UK, and Cao et al. (2017b) who introduce three end-uses for economy-wide cement use.

To introduce end-use detail, many of these studies use ‘end-use shares’, i.e. shares used to split total material consumption to different end-use products or sectors (see Figure 1 in Streeck et al. 2022). These end-use shares can be derived from two different data sources: first, data on material shipments to different industries or markets in mass units as reported by industry associations and statistical bureaus; and second, monetary input-output tables (MIOTs) which can be utilized to derive end-use information from monetary as proxy for physical data. Industry shipment data in mass units are scarce and most of the studies that make use of such data focus on a single material or country, or extrapolate information for few years and countries across the globe (e.g. Müller et al. 2006; Daigo et al. 2007; Pauliuk et al. 2013). MIOTs in contrast are widely available and their economy-wide nature, coverage of multiple sectors of material production, and compilation in global multi-regional input-output models (MRIOs), makes them an attractive data sources for deriving end-use shares for many materials, countries and years (e.g. Hashimoto et al. 2007; Chen and Graedel 2015; Pauliuk et al. 2017).

If we were able to combine information from these two data sources to derive end-use shares for a wide range of materials, countries and years, the application to economy-wide MFA databases, covering up to almost all global countries and a wide range of materials (UNEP 2016), could provide the quantification of material use in different applications at a novel material and country resolution.

Therefore in Streeck et al. (2022) we reviewed the literature that used industry shipments and MIOTs to generate end-use shares and theoretically assessed five different methods for their similarities, strengths and weaknesses. We concluded that the Waste Input-Output Approach to MFA (WIO-MFA) represents the most accurate choice to derive end-use shares from MIOTs, as it closely sticks to the mass-balance principle of dMFA, despite remaining limitations of MIOT-dMFA system boundary match (see Streeck et al. 2022 and section 2.1.1 for details). Furthermore, some methods other than WIO-MFA might still be attractive in some cases, due to their time-efficient application and despite their theoretical drawbacks.

Here we empirically apply the five identified approaches to derive end-use shares, as well as one suggested improvement, to compare derived results between methods, materials and end-uses. We deploy the methods to U.S. national MIOTs in a detailed comparison drawing on official national data with detailed product group resolution. Additionally, we apply the identified most accurate method to the regions of the MRIO EXIOBASE. Specifically, we aim to answer the following research questions:

* RQ1: How well do end-use shares derived from industry shipments in physical units and monetary input-output tables agree for the case of the USA and EXIOBASE regions?
  + RQ1.1: How well does the suggested improvement to WIO-MFA (‘Hypothetical Transfer)’ perform?
  + RQ1.2: Which differences across different materials and end-use products/sectors can be observed?
  + RQ1.3: What is the effect of sector and product aggregation on differences in end-use shares?
  + RQ1.4: How well do end-use shares from national data agree with end-uses derived from an MRIO?
* RQ2: What do the outcomes of RQ1 imply for obtaining end-use share information for many materials, years and countries for application to inflow-driven ‘top-down’ dynamic Material Flow Analysis?

# 2. Methodology

## 2.1 Summary of applied methods

In Streeck et al. (2022) we reviewed and systematized five methods to differentiate end-use products for economy-wide material flows based on data on industry shipments in physical units and monetary input-output tables (MIOTs). Additionally, we suggest one methodological improvement (‘Hypothetical Transfer’), overall making six methods that we here comparatively apply. Table 2 lists the key formulas of the methods, which we briefly describe in the following.

Table 1: Formulas and sources of the four input-output methodologies to derive end-use shares used in this study. For a detailed description of methods, please refer to Streeck et al. (in review).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Data | Approach | Key equations |  | Selected papers |
| Physical industry shipment | Direct use, (dis)aggregation of shipments (S) |  | (1) | Pauliuk et al. 2013; Liu and Müller 2013; Cao et al. 2017b |
| Monetary input-output tables | Waste Input-Output Approach to Material Flow Analysis (WIO-MFA) |  | (2) | Nakamura et al. 2007; Nakamura et al. 2014 |
|  | (3) |
|  | (4) |
| Consumption-based accounting (CBA) |  | (5) | (Hashimoto et al. 2007) |
| Ghosh Input-Output Approach to Absorbing Markov Chains (Ghosh-IO AMC) | , | (6,7) | Duchin and Levine 2010, 2013 |
|  | (8) |
| Partial Ghosh Input-Output (Partial Ghosh-IO) |  | (9) | Cao et al. 2017a; Aryapratama and Pauliuk 2019 |
|  | (10) |
| Hypothetical Transfer applied to WIO-MFA (HT-WIO) |  | (11) | own suggestion |
|  | (12) |

^ = matrix is diagonalized, -1 = matrix inverse**,** x = total product output, **L** = Leontief inverse, y = final demand, **D** = end-use share matrix, = material shipment to industry *i*, = technology matrix, = mass filter, = yield filter, index *m*,*p*,*c* = reference to partitioned matrices for materials *m*, intermediate products *p*, products delivered to final consumption *c*, **B** = matrix of allocation coefficients normalized to total output, **B**INTER = matrix of allocation coefficients normalized to intermediate output, = matrix for transferring transactions from **Z** to **Y** (see next subsection).

We use the summary term ‘industry shipments’ for statistics in physical units describing material deliveries to industry sectors or markets from which end-uses can then be inferred and assumed according to industry/market label (e.g. ‘construction’). Industry shipments often only cover parts of total material consumption (see Streeck et al. 2022 for detailed explanation). For that reason, many of the studies identified in Streeck et al. (2022) do not use industry shipments as direct input to dMFA models but instead calculate end-use shares by dividing individual by total shipments (eq. 1) and applying these shares to total material consumption, as we do here.

All methods using MIOTs distribute materials according to the monetary transactions from industry to industry (Partial Ghosh-IO) or from industry to final demand (all other MIOT methods), with differences in underlying IO-models and data manipulation between methods (Streeck et al. 2022). For all models presented here, proportionality between monetary and physical flows is default.

The Waste Input-Output approach to Material Flow Analysis (WIO-MFA) aims to track mass-balanced material and product flows with help of a Leontief price model. Therefore, the technology matrix representing economy wide transactions between industries is manipulated: filters are introduced to remove non-physical and waste transactions (eq. 2). In addition the technology matrix is partitioned in into two parts (eq. 3): one with coefficients only for transactions from material to product sectors, and the other with coefficients only for transactions from product to product sectors. These features allow WIO-MFA to approximate material and product flows at their actual mass, instead of calculating footprints. The end-use share matrix is calculated by dividing deliveries to final demand per product by total product output (eq. 4).

The Consumption-based Accounting approach (CBA) calculates material footprints following the (environmentally extended) Leontief quantity model and uses supply-chain wide multipliers (eq. 5). That means that the allocation of material flows entails embodied materials over the whole supply chain, not removing transactions that refer to waste or non-physical flows. As for WIO-MFA, is calculated by dividing deliveries to final demand per product by total product output. In equation 5 we only use the monetary data to compute end-use shares, without considering environmental satellite accounts.

The Ghosh-IO approach to Absorbing Markov Chains (AMC) combines a Ghosh quantity model with fixed sales structure with the input-output market balance (shares of final demand on total output as the Markov absorbing state; eq. 6-8). Like WIO-MFA, Ghosh-IO AMC partitions transactions between materials and products (eq. 6). The Partial Ghosh-IO approach in contrast does not use final demand accounts but only relies on the interindustry matrix, for which the practitioner defines absorbing states as a set of sectors in this matrix (eq. 9). The basic element of both Ghosh-type approaches is the allocation matrix , with its coefficients representing sector market shares (mind the different definition of between methods in Streeck et al. 2022). For Partial Ghosh-IO the end-use share matrix is readily obtained as part of a Ghosh-type inverse (eq. 10), while for Ghosh-IO AMC the inverse is multiplied with the absorbing state (final demand shares). For detailed conduct of methods please refer to part I of this publication (Streeck et al. 2022).

Of all described MIOT-based methods, WIO-MFA adheres most closely to an MFA logic and can be regarded as most accutrate for evaluating end-use shares from a theoretical point of view (Streeck et al. 2022). However, as discussed in Streeck et al. (2022), also WIO-MFA has limitations. Therefore, we additionally introduce a fifth approach to MIOTs call this method ‘Hypothetical Transfer (HT)’, which we here apply to WIO-MFA (‘HT-WIO’). This suggested method variation and the limitation it addresses is described in section 2.1.1.

### 2.1.1. Methodological suggestion: ‘Hypothetical Transfer’ applied to WIO-MFA (HT-WIO)

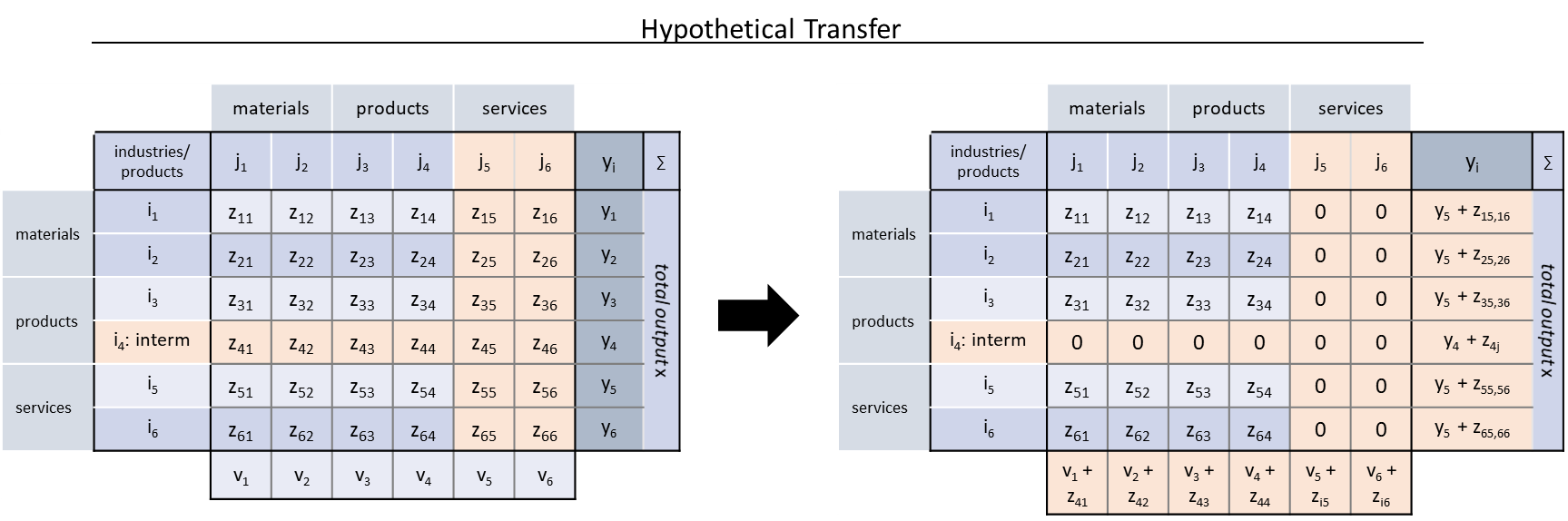
All MIOT-based methods that determine the end-use of materials according to the products these are contained in when being delivered to final demand come with a potential limitation: in particular cases when calculating the supply-chain distribution of materials to products (the inverse), the end-use meaning of products can be lost due to non-matching system boundaries of MIOTs and dMFA (see Streeck et al. 2022). For instance, products such as ‘packaging’ are end-uses (= final demand) in the sense of dMFA but are classified as intermediate demand in MIOTs. Thus the materials (e.g. ‘plastics’) contained in these intermediate products (e.g. ‘packaging’) are accompanying other products (e.g. ‘motor vehicles’) delivered to final demand. When calculating the supply-chain tracing via Ghosh/Leontief inverse, ‘plastics in packaging’ delivered to ‘motor vehicles’ is missclassified as ‘plastic in motor vehicles’. Above issue can apply for MIOT transactions between sectors representing physical products (the ‘packaging’ example), but also between a sector representing a physical product and a service sector. ‘Plastics in packaging’ might then for instance end up in the end-use ‘hotels and restaurants’, the physical use of which could only be guessed. [[1]](#footnote-1)

There are three ways to resolve missclassification as ‘service’, while only one for assignment to the wrong ‘product’: 1) for ‘service’ one can ‘guess’ the end-use by assuming for instance that ‘plastics’ delivered to ‘hotels and restaurants’ end up as food packaging (like e.g. done in Cao et al. 2017a), 2) one can simply delete the transactions to ‘service’ sectors like might seem intuitive for WIO-MFA (unfortunately no study transparently reports steps from original to mass-filtered MIOTs so that dealing with ‘services’ can only be assumed), or 3) one might apply methods similar to production layer decomposition to re-instate the end-use functionality of upstream inputs (works for misclassification as ‘product’ and ‘service’).

Case 1) seems ill-advised as it introduces subjective assumptions. Case 2) biases the distribution of materials to end-use products, as the upstream supply-chain ‘pull effect’ from the ‘service’ sectors’ final demand is neglected. Thus only case 3) seems feasible and at least two methods exist to correct for misclassifications: the Hypothetical Extraction Method as applied by (Yokoi et al. 2018; Dietzenbacher et al. 2019; Hertwich 2021) and production layer decomposition as supposed by (Nakamura et al. 2007). However, all of these approaches imply initial double counting, if MIOTs are not perfectly triangular (directional). This can be corrected for (see Cabernard et al. 2019; Hertwich 2021), which however comes with assumptions and tedious work, which seems hardly applicable to all products of detailed MIOTs such as the national U.S. benchmark MIOTs.

Therefore, we here propose a simple approach that corrects for missclassifications by transferring direct flows of target transactions to final demand and term that method ‘Hypothetical Transfer (HT)’: the total flow matrix is used to transfer the transactions considered as intermediate (e.g. the total output of ‘packaging’ by MIOT sector, or output of a ‘product’ to ‘service’ sectors) to final demand (Figure 2, eq. 11-12). This way the intermediate products of interest formerly endogenous to the interindustry system are exogenized to final demand, thereby keeping their end-use functionality during inverse calculation. One could also express this procedure as cutting off the system boundary of the interindustry system towards downstream. The proposed operation does not change the MIOT market balance, as values are simply relocated within the balance without change in total sector output (transactions for rows transferred from to ). The missing input to the industry balance is assumed to be covered by additional value added (transactions for columns from to ).

When using this method in conjecture with WIO-MFA, yield filters should be applied to (instead of ) before Hypothetical Transfer, to avoid the assignment of ‘waste flows’ to final demand (eq. 11-12). For a simple matrix algebra example please refer to the supplementary information two (SI2).



*Figure 1: Example for the Hypothetical Transfer (HT) method applied to an example monetary input-output table (MIOT): during hypothetical transfer, the direct flows of products that are intermediate demand in the logic of the MIOT but end-use (final demand) in Material Flow Analysis, as well as monetary flows that most probably correspond to a physical counterpart but are input to services sectors, are transferred from the interindustry flow matrix to final demand . One could say that the interindustry supply chain is cut-off towards downstream by re-classifying intermediate outputs as final demand (end-use).*

## 2.2 Data sources

Table 2 shows the data sources for U.S. industry shipments and MIOTs, as well as their temporal coverage and end-use resolution. The industry shipment data comes with several limitations detailed in Streeck et al. (2022). To notice for the U.S. in particular are: for both data sources on Copper, the end-use ‘buildings construction’ contains construction machinery (USGS 2015; CDA 2020); USGS (2015) iron & steel data is only partially useful as 62-73% of total shipments are reported to the end-uses ‘service centers and distributors’, ‘undistributed’, or ‘other’; for iron & steel the American Iron and Steel Institute (AISI 1941-2005) data as reported by Pauliuk et al. (2013) only reports 50% of steel shipped to domestic crude steel production; for iron & steel the YSTAFB data (Myers et al. 2019) leaves unclear which end-use shares rely on AISI reported values; for wood, the data by McKeever (2009) was generated partially drawing on economic data, which cannot deliver a completely independent picture in comparison to input-output generated end-use shares and gives volumetric not mass end use shares which we converted using factors from FAO (see SI); and where indicated in Table 2, material contained in final goods trade was added from data obtained in Streeck et al. (2021).

Table 2: Material, time and end-use resolution for industry shipment data sources, as well as national level monetary input-output tables (MIOTS) for the USA, and the multio-regional input-output model EXIOBASE.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Source | Period | End-uses | Comment |
| Industry shipments | | | | |
| Aluminum | USGS (2015) / AAI (1976–2003) | 1975-2003 | (Building &) construction, Consumer durables, containers and packaging, electrical, machinery and equipment, transportation, other | USGS data based on AAI end-use shipment shares applied to USGS data on apparent consumption; added net trade in final products from Streeck et al. (2021); yield correction applied |
| Liu and Müller (2013) | 1960-2009 | From Global Aluminium Recycling Model; yield correction applied |
| Cement | PCA (2016) | 2011-2015 | Public construction, nonresidential buildings, residential buildings, other (all with 4-7 subcategories) | - |
| Cao et al. (2017b) | 1992-2016 | Civil engineering, nonresidential building, residential building |
| Kapur et al. (2008) / PCA (2005) | 2003 | Residential buildings, public buildings, commercial buildings, water and waste management, streets and highways, farm construction, utilities, others |
| Copper | USGS (2015)/CDA (2020) | 1975-2003 | Building construction, Consumer and general products, Electrical and electronic products, Industrial machinery and equipment, Transportation equipment | CDA shares applied to US primary copper apparent consumption; Added net trade in final products from Streeck et al. (2021) |
| CDA (2020) | 1999-2019 (as available) | tracks gross metal shipments to end use markets (more comprehensive); Added net trade in final products from Streeck et al. (2021) |
| CDA (2022) | 1994-2002, 2008-2010 | Building wire, plumbing & heating, power utilities, automotive electrical, air conditioning & commercial refrigeration, telecommunications, in-plant equipment, business electronic, ordnance, lighting & wiring devices, other (slight changes over years) | - |
| Iron & steel | USGS (2015) / AISI (2003) | 1975-2003 | Construction, Containers, Other, Service centers and distributors, Transportation, Undistributed | Large fraction to service centers and undistributed; Added net trade in final products from Streeck et al. (2021) |
| Pauliuk et al. (2013) / AISI (1941-2005) | 2004 | Aircraft, agriculture, appliances, automotive, construction, containers & shipping materials, electrical equipment, machinery, mining and quarrying, oil and gas industry, ordnance and other military, other domestic and commercial equipment, rail transportation, shipbuilding | Only represents 50% of shipments to domestic crude steel production |
| YSTAFB (Myers et al. 2019) / Müller et al. (2006)/ AISI (1941–1999) | 1941-1999 | Construction, machinery & appliances, other products, transport | Original data not published; unclear for which years primary data was used |
| Plastics | Euromap (2020) | 2009-15 | Automotive, construction industry, electrical electronics and telecom, packaging, other | Unclear whether physical/downloaded; data was downloaded in 2020, now members-only |
| Tin | USGS (2015) | 1975-2003 | Cans & containers, electrical, construction, transportation, other | Data sourced from USGS and U.S. Bureau of Mines; apparent consumption |
| Wood | McKeever (2009) | 1950-2006 | New housing (single family, multi family, manufactured), residential repair & remodeling, new nonresidential (buildings, other), manufacturing (furniture, other), packaging & shipping, other | Data result of estimation process including use of monetary data; yield correction applied for end-use ‘furniture’ |
| U.S. national MIOTS | | | | |
| 12-19material | US BEA (2018,2021) | 1963, 1967-2012 (5-yearly) | sectors for 2012 MIOT (exemplary): 28 construction, 64 machinery, 26 transport, 8 household appliances, 8 furniture, 8 textiles, 5 packaging, 29 food, 19 extraction, 135 services, 75 others | Sector classification changes over time; yield correction for WIO-MFA according to yield filter matrices |
| EXIOBASE (44 countries + 5 rest of world regions) | | | | |
| 15 materials | Stadler et al. (2021) | 1995-2011 | Sectors: 1 construction, 5 machinery & appliances, 2 transport, 1 furniture & others, 3 textiles, 26 agriculture & food, 27 raw materials, 22 energy carriers, 66 services, 48 others | Yield correction for WIO-MFA according to yield filter matrices |

\*for remaining industry shipment materials USGS only reports intermediate categories (e.g. for lead, zinc, cement); plastic end-use data in theory available from ‘Resin Review: The Annual Statistical Report of the North American Plastics Industry’ (ACC), but payment basis

Industry shipment data for countries other than the U.S. were available from the sources listed in SI 1.1. In general little long-term data are available on the country level. The ones we found distinguish between 5-10 end-use categories: information for 20 countries and 9 world-regions for aluminum (Liu and Müller 2013; Bertram et al. 2017), 184 countries for cement ca. 1990-2011 (Cao et al. 2017b), copper for North America and EU28 (Spatari et al. 2005; Ciacci et al. 2017), iron and steel for China, India, UK, USA (Dahlström et al. 2004; Pauliuk et al. 2012, 2013), and plastics for ca. 63 countries for 2009-15 and longer for China and EU (Euromap 2016; Jiang et al. 2020; Plastics Europe 2006-2021).

Regarding MIOTs, we herein utilize national MIOTs for the USA, as well as the state-of-the-art multi-regional input-output model EXIOBASE. U.S. national MIOTs were derived from the U.S. BEA benchmark supply-use tables/MIOTs (US BEA 2018, 2021), which are available at a very high sectoral resolution (367-537 sectors) for the years 1963 and every five years from 1967 onwards until 2012. For comparison, and considering a globally available source for other countries we used EXIOBASE v3.8.2 as published by Stadler et al. (2021).

## 2.3 Technical implementation and testing sensitivity in scenarios

The details of the preparational steps required to calculate end-use shares with the methods in Table 1 are described in the supplementary information (SI 1.2) and summarized here. The scripts and underlying data for calculation of results from MIOTs are available on GitHub (insert link to repository).

Predominantly, we used industry shipment data without further manipulation. Only for cases in which it was clear that system boundaries required adjustment to calculate domestic end-uses we applied the following operations: 1) when shipments did not include trade in final products (indicated in Table 2) we added UN Comtrade data derived from Streeck et al. (2021), and, 2) when we could be certain that shipments referred to crude materials for which substantial processing losses during manufacturing to final products could be expected, we subtracted processing losses as reported in the WIO-MFA yield matrices (see SIX). The end-use was inferred by the labeled destination of shipments (e.g. ‘construction’).

For MIOTs the practitioner needs to make several choices for calculating end-use shares: 1) which parts of MIOT accounts to use to represent domestic material use, 2) how to identify sectors assumed to distribute materials and products to end-use, and, 3) how to manipulate MIOT data to approximate physical flow behavior for monetary transactions.

1. For both USA national and EXIOBASE MIOTS, we used reported accounts for domestic and imported interindustry flows and final demand (excluding exports and inventory changes).
2. For MIOTs we had to choose the sectors that represent material and end-use from the entire sector list. We selected sectors representing material use according to sector label and description (for the USA in NAICS (2017)) that closest matched the properties of a potential material extension. For example, we designated the sector ‘iron & steel production’ as the sector distributing the domestic use of crude steel material flows to downstream MIOT sectors. For the U.S. tables, several sectors potentially qualify for distributing material flows. Therefore, we calculated end-use shares for two sets of sector selections and evaluate their influence on results (see SI 1.2.2 for sets; default is ‘Base’). Similarly, we identified the end-use of sectors according to their label. USA MIOTs show very high sector resolution and could in theory distinguish hundreds of product groups. For presentation of results, we aggregated end-use sectors (after calculations) to 18 end-use categories and allocated each sector output to these categories according to sector label. For the USA we additionaly consulted the description in NAICS (2017) as well as allocation in Chen (2017). Please note that end-use categories are not necessarily entirely exclusive: for instance, products such as ‘prefabricated buildings’ are part of either ‘residential structures’ and ‘non-residential structures’ but could not unambiguously allocated to one of the latter and were thus classified under the category ‘other buildings’.
3. All MIOT-based approaches to calculate end-use shares except for CBA require the definition of filter matrices. Filter matrix configurations and scripts to assemble filters are documented on GitHub. For WIO-MFA, two types of filter matrices need to be designed: the mass filter and the yield filter. The mass filter removes monetary transactions/flows that are believed to have no physical counterpart, such as service flows. The decision on whether to filter, i.e. set to zero, or keep a specific transaction remains subjective to some degree. To capture the ambiguity we designed two scenarios: one in which service sector in & outputs were deleted (called ‘WIO-MFA’; default) and one in which only service sector outputs were deleted (called ‘WIO-MFA\_filtDif’). Ghosh-IO AMC filters were designed as described in Duchin and Levine (2010): no mass or yield filters were applied but reverse transactions from products to materials were prohibited and the final demand of sectors selected as ‘materials’ were set to zero. For the Partial Ghosh-IO filter, products need to be differentiated into intermediate and end-use products. We followed th reasoning of Aryapratama and Pauliuk (2019) who evaluate the differentiation in their case study according to the ratio between the value of product output going to intermediate versus final demand. For all details please refer to SI 1.2.3.

# 3. Results

## 3.1 USA

Results below refer to USA national MIOTs and shipments in Table 2, if not labeled otherwise. The figures below only show MIOT-based results on the level of sector aggregation that matches the categories of the physical unit industry shipments. We found 115 time series or data points of material end-use industry shipments for comparison to MIOT-based results. Here we compare to 54 of these data series, the remainder depicting either very detailed categories that were aggregated for comparison, or categories such as ‘other’. For additional results please see SI and GitHub repository.

### 3.1.1 Comparison of HT-WIO to industry shipments at low sector resolution (RQ 1, 1.1, 1.2)

In 2.1.1 we presented HT-WIO as the most accurate MIOT-based approach to trace material flows to end-use products. In Figure 2, we compare the results of this method for different materials, end-use categories and the U.S. national MIOTs, as well as EXIOBASE, to available industry shipments (plus additional results for other MIOT-based methods). The values in the upper right corner of subplots refer to the relative deviation of HT-WIO results with U.S. national MIOTs from shipments (median, minimum, maximum).

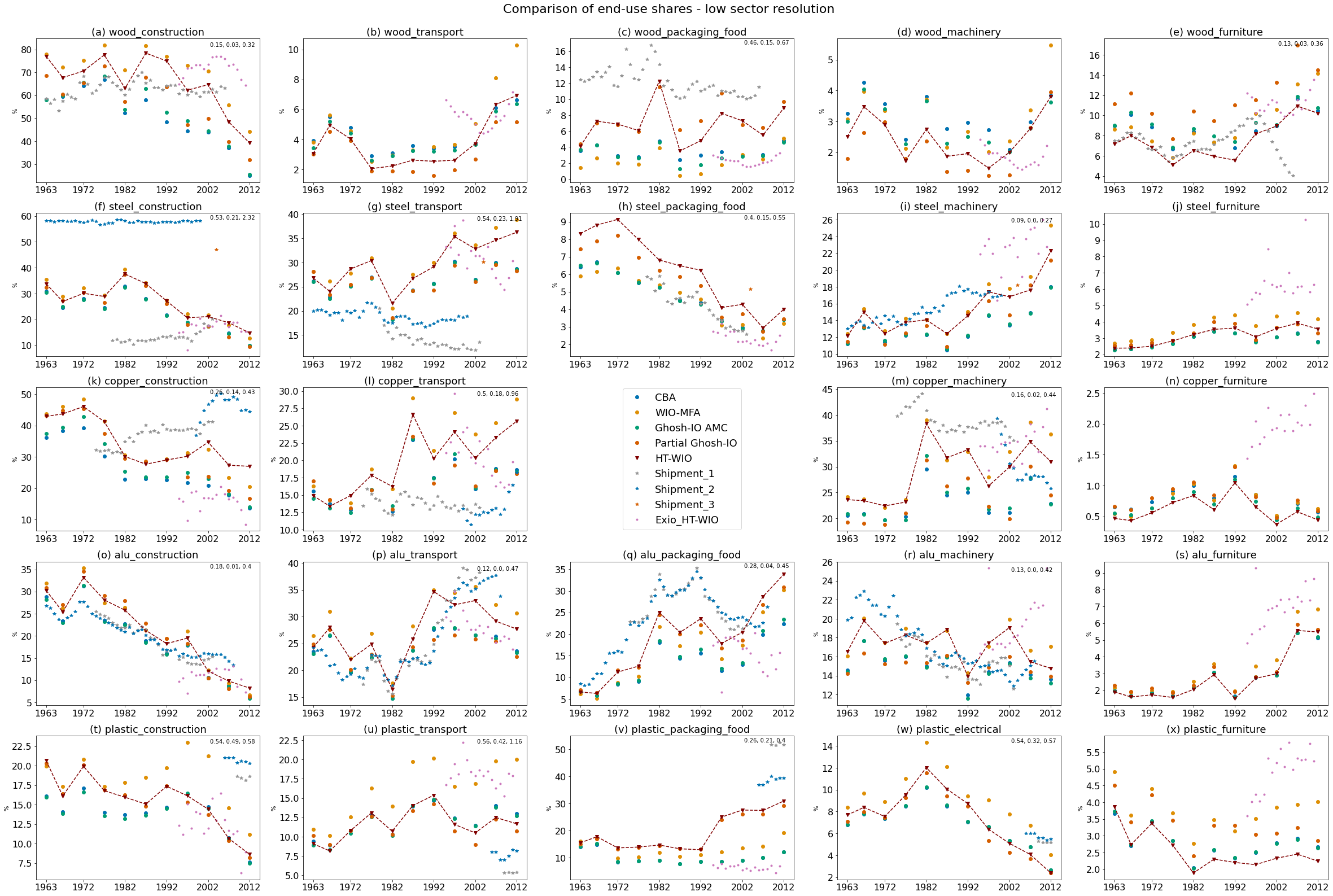


Figure 2: Comparison of end-use shares derived from U.S. monetary input output tables (MIOTs) for 11 data points between 1963-2012 generated with five input-output approaches and industry shipment data in physical units (see section 2) at low sector resolution (results aggregated to 18 sectors after calculations). Values in the upper right corner of subplots refer to the relative deviation of HT-WIO results from shipments (median, minimum, maximum). For the methods to MIOTs, specific sectors were selected to represent material distribution as end-use shares. To see which sectors were considered to correspond to the shown materials ones were for each year, please see the SI 1.2.2 ‘Base’ scenario.X . The shown data sources for industry shipments are (Table 2): wood - all: McKeever 2006; steel – 1: USGS, 2 – YSTAFB, 3 – Pauliuk et al. 2013; aluminum: 1 – USGS, 2 – Liu et al. 2013; copper: 1 – USGS, 2 – CDA; plastic: 1 – Euromap, 2 – Plastics Europe (data for EU not US)

In text, we additionally describe the deviation over more than one subplot as the . The relative deviation of HT-WIO results in comparison to industry shipments over all materials, end-uses and years was . However, this deviation is biased by the differing availability of industry shipments per material and end-use. Therefore it seems more instructive to look at deviation of individual materials, end-uses or combinations thereof.

When looking at the difference between materials, HT-WIO results for aluminum show the the best (relative deviation ,) while steel shows the worst fit to industry shipments (). The poor match for steel is to some degree due to the poor quality of steel industry shipment data, indicated by strongly diverging values for shipment sources (panels f & g). Looking at the comparison between end-use categories, differences are smaller than between materials, with machinery & electrical being closest to shipment data with a relative deviation of , and transport deviating strongest with .

For individual subplots, we find rather good fit for, for example, aluminum in construction (panel o) or wood in furniture (panel e) and rather bad fit for, for example, steel in construction (panel f) or wood in packaging (panel c).

Despite large deviations for many material end-uses, the temporal trajectories of 13 MIOT-based end-use shares approximate those of industry shipments, if also deviating in magnitude and sometimes lagging in time (good fit for aluminum in construction and packaging (panel o & q), and rather good fit for e.g. copper in construction & transport (panel k & l), and aluminum in machinery (panel r)). Exceptions are for instance wood in furniture after 2002 (panel e) and steel in construction (panel f). For 4/18 plots with shipment data we could not judge the temporal fit due to the short time series of shipments. For figure and statistical data please see the Data SI 1.

### 3.1.2 Comparison of different MIOT-based methods

Figure 2 also shows results for the MIOT-based methods CBA, Ghosh-IO AMC and Partial Ghosh. Differences across methods originate from varying underlying system boundaries through (non-)manipulation of MIOT structure and data through differing definitions of absorbing states, mass filters and yield correction (section 2.1 & Streeck et al. 2022). From the comparison of methods, two prominent observations can be drawn:

First, although the methods of CBA and Partial Ghosh-IO are simple when compared to HT-WIO (no mass and yield filters, little supply-chain flow manipulation), both methods perform surprisingly well, when comparing to HT-WIO results. For many materials and end-uses, these methods are close to HT-WIO results (e.g. panels (b, f, o, u)). However, this does not imply that these methods are suited from a conceptual point of view with, for example, CBA calculating embodied instead of actual mass, leading to large deviations for some plots (e.g. panels (a, m, p, x)).

Second, strong deviation between methods can be observerd in particular for the end-use ‘packaging/food’. Here, the MIOT system boundary problem outlined in section 2.2 can be observed in action. Packaging is an ‘intermediate product’ in MIOTs, while an ‘end-use product’ in the sense of dMFA. HT-WIO has been introduced to tackle this issue, while other methods that do not consider this problem perform worse for packaging end-use shares (Figure 2, 3rd panel column). For these methods, materials contained in packaging are effectively incorporated in downstream product mass (e.g. plastics in car packaging accounted for as plastics in car). The described phenomenon can be observed in particular for wood and plastics packaging (panels c&v) but is less pronounced for metals packaging (panels h&q). However, this would change if we did not interprete the use of above materials in ‘food products’ as ‘packaging’ too (e.g. makes up 5-30%-points of aluminum packaging accounting in WIO-MFA over all years). A methodological exception is Partial Ghosh-IO, as in there the ‘absorbing’ end-use state is directly defined by the practitioner from matrix flows, and thus ‘packaging’ can be assigned as end-use, like we did here. The results are very similar to HT-WIO. Correctly accounting for MIOT ‘intermediate products’ such as packaging does not only influence the end-use shares of these ‘intermediate products’, but also leads to overestimation of shares of all other end-uses, as in neglect these get assigned higher shares (i.e. if shares if one end-use change that means that shares of all otehrs change too). This gives a rationale for using the proposed HT-WIO method. For additional details and explanations please refer to SI 1.3.1.

### 3.1.3 Comparison of different input-output databases (RQ 1.4)

The difference of MIOT-based end-use shares from official national MIOTS and the MRIO EXIOBASE varies between material end-use combinations (Figure 2). While well aligned for steel in construction and for part of the time series of aluminum and plastic in construction (1st panel column), as well as for steel, aluminum and copper in transport (2nd panel column); rather large deviations occur for certain years or periods of latter panels. Partially, opposite trends and large outliers can be observed (e.g. panel (l): outlier in 1997 and large deviations since 2005). Performance is particularly bad for furniture (5th panel column; except wooden) but also for packaging which EXIOBASE does not distinguish as separate end-use sector (3rd panel column). Metals packaging is an exception as the lacking packaging sectors is compensated by considering deliveries to food sectors as packaging (food products are a primary application of metal packaging; plastics and wood packaging in contrast used for diverse end-use products). Also for comparison of EXIOBASE-based results to industry shipments a mixed picture emerges. Thus judging from a first comparison to national MIOT data and U.S. shipments, EXIOBASE performs reasonably well for some material end-uses while bad for others, without showing a clear systematic except for overestimation of ‘furniture’ end-use shares and underestmation of ‘packaging’ other than metallic.

### 3.1.4 Comparison HT-WIO to industry shipments at varying sector resolution (RQ 1.3)

One potential advantage of using the U.S. MIOTs is that we could potentially achieve very high resolution of end-uses (see Table 2). Here we compare U.S. MIOT-based results at different levels of end-use resolution to available shipment data. Figure 3 depicts the wood and cement use at medium detail (‘civil engineering’, ‘residential’ and ‘nonresidential structures’), and high detail (which corresponds to individual MIOT sectors; ‘single-family’ and ‘multi-family’ ‘buildings, housing and structures’). At these levels of detail, industry shipment data for comparison is scarce, i.e. we only found data for the U.S. wood and cement (and for a single year for steel, and more years for copper, however with uninformative end-use categories; Table 2). Two things are important when interpreting Figure 3 results:

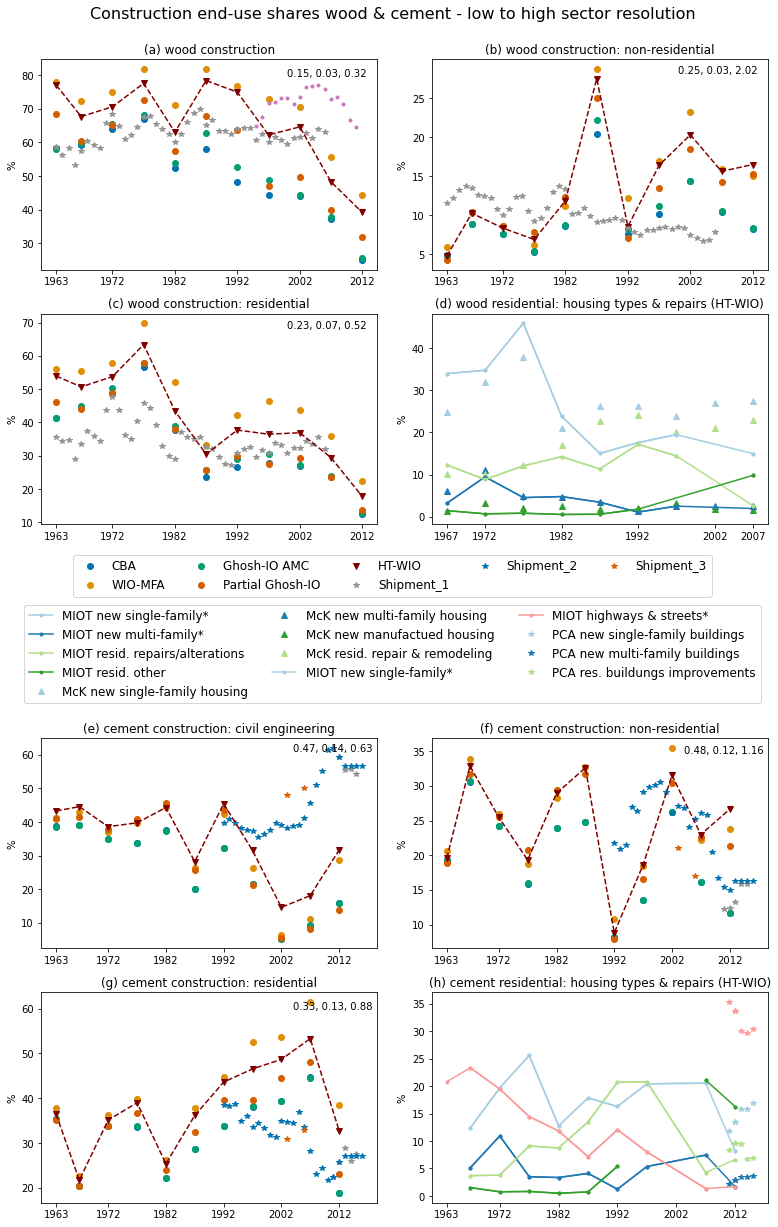


Figure 3: Comparison of end-use shares derived from U.S. monetary input output tables (MIOTs) for 11 data points between 1963-2012 generated with five input-output approaches (see section 2.1), with industry shipment data in physical units (see section 2.3) at medium (1) and low (2) sector aggregation. The shown data sources for industry shipments are (Table 3): wood - all: McKeever 2006 (McK); cement – 1: PCA, 2 – Cao et al. 2017, 3 – Kapur et al. 2008. Please note that the end-use categories of MIOTs do not exactly match those of industry shipments (indicates by the asterisk\* in the second legend): PCA – ‘buildings’; McKeever ‘housing’; MIOTs - ‘buildings’ (1963), a mix of ‘housing’, ‘apartments’ & ‘buildings’ (1967-1977); and a mix of ‘structures’, ‘apartments’ & ‘buildings’ (1982-2012). Thus also on the medium-level aggregation (residential, non-residential, civil engineering) these classification mismatch applies. For details please see text below figure.

First, the definitions of each end-use category between the four data sources differ: the Portland Cement Association (PCA) talks about ‘buildings’, McKeever (McK) talks about ‘housing’, Cao et al. (2017) talk about ‘building’, and the MIOTs discern ‘buildings’ for 1963, a mix of ‘housing, apartments & buildings’ for 1967-1977, and a mix of ‘structures, apartments & buildings’ for 1982-2012 (see GitHub for Excels with MIOT and industry shipment end-use category / sector definitions). None of these categories are defined in original sources, leaving unclear which activities are aggregated under these terms.

However, the MIOT-based end-use shares for asphalt hint towards the system boundaries for MIOT-sectors: large end-use shares of the material sector ‘paving mixtures’ are calculated for the construction categories (e.g. ‘single- and multi-family structures’ in 2007/12: 15-35% of ‘paving mixtures’ end-uses; ‘new office buildings’ in 1982: 11%), which suggests that the MIOT categories ‘buildings, housing and structures’ include urban streets for which these ‘paving mixtures’ are used. This raises a classification problem, as for dMFA we would like to distinguish material use in buildings versus streets, as these stocks provide very different services.

Second, at the end-use resolution ‘construction’, we assume categories such as ‘ready-mix concrete manufacturing’ (6-8% of 2012 cement use) or to contribute ‘residential alterations and repairs’ (between 4-21% of cement use from 1963-2021, Figure 3). However, at higher resolution, we cannot allocate concrete to either (non-)residential or civil engineering, or residential repairs to single or multi-family housing. Thus the end-use shares at comparatively high sector resolution (panels b-h in Figure 3) only include material use that is unambiguously associated and might therefore underestimate shares.

For wood, we find good fit for the low-resolution end-use ‘construction’ (median deviation of 15%), with a temporal trajectory similar to shipments. Disaggregating ‘construction’ into the sub-categories ‘residential’ and ‘non-residential’ (panles b-c), we find rather good fit for longer time periods but large single or multiple-year deviations of >50-200%. Further zooming into individual MIOT sectors (panel d), we observe a rather good fit again, with a deviation of 27% (min. 8, max. 45%) for ’new single family\*’ and 10% (min 2%, max. 48%) for ’new multifamily\*’.

For cement, we do not show the category ‘construction’, as we assume that 100% of cement is delivered to this categoriy (in HT-WIO results 91-99% among years). When disaggregating ‘construction’ into the end-uses , we find deviations ‘civil engineering’, ‘non-residential’, and ‘residential’, we find rather large median deviations between 33-48% (and larger outliers with 63-116%), albeit coarsely similar temporal trajectory. These large deviations are probably due to missclassification of cement in ‘highways & streets’ as ‘residential and urban structures’ in MIOTs as explained for asphalt ‘paving mixtures’ above. This is also visible in panel (h): for 2012 the MIOT sector ‘transportation structures and highways and streets’ is assigned <2% of cement use, which stands in stark contrast to 34% of cement use reported by PCA industry shipments to ‘highways and streets’. In panel (h), the median deviation of MIOT and PCA data for 2012 are 95% for ‘highways & streets\*’, 39% ’new single family\* and 41% for ’new multifamily\*’.

### 3.1.5 Sensitivity to choices of supply or use sectors & filter matrix

The choice of supply or use sectors in MIOTs, as well as WIO-MFA filter design (we can also call it MIOT data manipulation) are two methodological choices expected to effect results rather strongly (Nakamura et al. 2009; Owen et al. 2017; Wieland et al. 2020). Therefore we ran a second set of supply/use sector and filter choices for the methods WIO-MFA and HT-WIO (see section 2.3). Results showed that for both items large deviations compared to the base case can occur, underlining the importance of supply/use sector and mass filter choices (see SI for details).

## EXIOBASE

Figure 4 panels 1a-I compare MIOT-based results with available industry shipment data in physical units for China, India and the UK as the countries with many shipment datapoints. Panels 2j-l map HT-WIO results for three selected material end-uses for all 49 EXIOBASE regions and identify countries with minimum and maximum values. For plot data, including the (relative) differences between MIOT-based and shipment results, please see Data SI for Figure 4.

For panels 1 steel, we find rather good fit of shipments to MIOT-results for China (also for machinery & appliances, for which the two shipments refer to one item each and are within range of 30% relative deviation except for outliers in 2004/6), Indian and UK machinery, and Indian transport, while MIOT-results strongly underestimate steel use in construction for India (-48 to -87%) and even stronger for UK (-73 to -82%). For aluminum we observe okay to good fit for China and India, with exception of Chinese transport (-54% to +20%), and rather bad fit for the UK. Strikingly, machinery & appliances are strongly overestimated in MIOT-results for all three countries (with all except 3 data point deviations >200%; summary of MRIO sectors 'Machinery and equipment n.e.c. ' and 'Medical, precision and optical instruments, watches and clocks'). This also applies to 10/11 additional country comparisons with shipment data from Liu and Müller (2013) (see SI 1.3.3). For plastics, we can observe that the largest end-use according to shipment data (‘packaging’) has no representation in EXIOBASE.

For panels 2, we observe wide ranges of end-use shares among countries for steel use in construction and transport, and aluminum use in construction. Countries with high shares for construction aluminum are Japan and Greece (low shares quite mixed; Russia 2x), for construction steel Indonesia and Taiwan (low shares for UK and Malta), and for transport steel Luxembourg and Brazil (low shares Russia). Data from Liu and Müller (2013) confirm low construction aluminum shares for Russia, and rahter high shares for Japan, although shares for Netherlands and Norway are much higher (see SI 1.3.3). Unfortunately steel shipment data is very scarce and no comparison except for the UK can be conducted (for UK low MIOT-based construction steel shares seem to be an artifact; see panel 1c). Please note that the box / swarmplots are not weighted by the material consumption volume of respective countries.

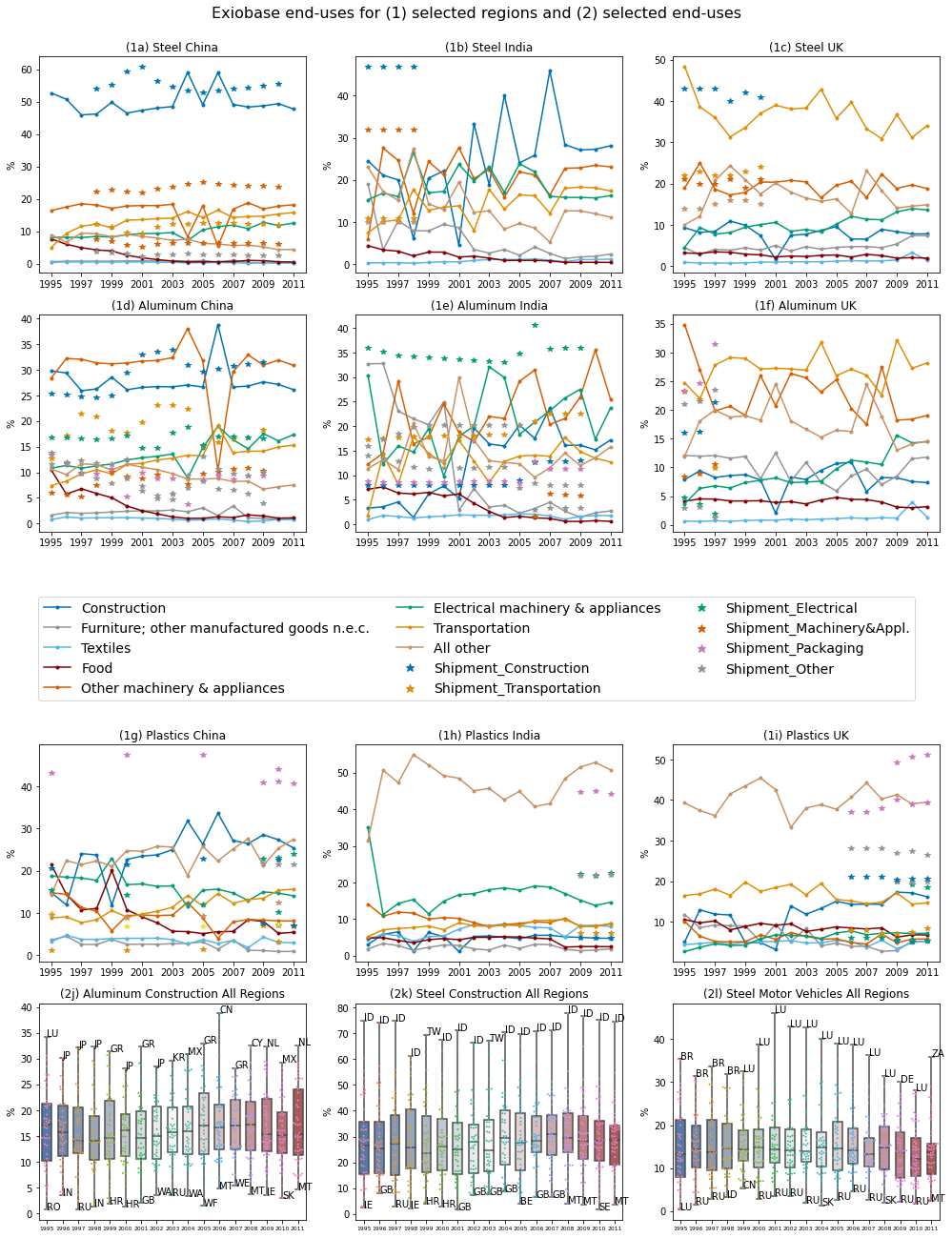


Figure 4: Comparison of end-use shares derived from EXIOBASE with the method of HT-WIO (see section 2.3), with industry shipment data in physical units (see section 2.3). The shown data sources for industry shipments are (Table 4): steel: China – Pauliuk et al. 2012, India – Pauliuk et al. 2013, UK -Pauliuk et al 2013/Dahlström 2004; aluminum: all – Liu & Müller 2013; plastics: China – Jiang et al. 2020/Euromap 2016, India – Euromap 2016, UK - Euromap 2016/ Plastics Europe 2006-2021 (shares for whole EU). BE = Belgium, BR = Brazil, CN = China, CY = Cyprus, DE = Germany, GB = United Kingdom, GR = Greece, HR = Croatia, ID = Indonesia, IE = Ireland, IN = India, JP = Japan, KR = South Korea, LU = Luxembourg, MT = Malta, MX = Mexico, NL = Netherlands, RO = Romania, RU = Russia, SE = Sweden, SK = Slovakia, TW = Taiwan, WA = Rest of World Asia and Pacific, WE = Rest of World Europe, WF = Rest of World Africa, ZA = South Africa

# Discussion of insights from empirical application

* Purpose of this work was to compare the end-use shares derived with different MIOT-based methodologies to industry shipments in physical units and see the fit
* And from this to draw conclusions on the best method and potential to derive end-use share information for many materials, countries and years

## How well do end-use shares derived from MIOTs versus industry shipments agree?

* HT WIO as theoretically best method (Simple methods like CBA or particularly partial Ghosh might still be a quick-and-dirty first guess) but in practice we saw varying fit to industry shipments
  + Differences between materials for U.S. MIOT-results (alu good, wood rather good, steel bad)
  + For large part of material end-uses the temporal trajectory was similar
    - So MIOTs might give information about temporal changes, also if not about exact magnitude
    - Raises the idea to calibrate overlapping periods of MIOT-based results with industry shipments and then use the trajectory
  + Difficult to draw overall conclusions, as agreement seems to depend on the specific material end-use combinations for countries and years
* Therefore, wherever possible should be compared to physical data; potentially also from other countries and qualitative data trying to validate results (e.g. does it make sense that end-use shares for steel to construction are lower in the UK than in the US given their preferred building types, construction preferences and standards?)
* But keep in mind that also physical data has its limitation (see diverging shipment sources in Figure 2 and paper part I)
  + Hower also: In general, industry shipments cannot be regarded as a reliable benchmark for MIOT results, as they come with several limitations that make this data uncertain (for instance, for USGS steel shipment data, 62-73% of total shipment mass are reported to categories with unknown end-use, e.g. ‘service centers’; for additional explanation on limitations see Streeck et al. 2022).
* What could change for better agreement?
  + importance of end-use sector defintions and system boundaries (often unclear!) 🡪 we might end up comparing apples and pears
    - We need to recall that the aggregation of MIOT sectors to the shown end-use categories relies on practitioner decisions (for our choice see GitHub repo) and that the system boundaries of MIOT end-use categories do not necessarily fully align with those of the industry shipments (for these system boundaries hardly reported).
  + Methods other than HT-WIO ignore ‘intermediate products’ in end-use shares, which biases results of all end-uses
    - e.g. packaging as an important end-use for materials like plastics, aluminum, glass
    - precondition for working HT-WIO for packaging is that this sector is differentiated in MIOTs
    - also if this is not the case HT-WIO produces more reasonable results, as the deliveries of products to service sectors are accounted as final demand (eliminating meaningless ‘services’ as end-use category, thereby not biasing shares of other, meaningful end-use product categories)
    - we suggest that just deleting the inputs to service sectors biases results as the ‘upstream pull-effect’ of service demand is deleted (outputs in turn can and should be deleted as these most probably do not correspond to physical flows
  + all data sources must improve; transparent reporting and also s; even for US MIOTs the construction sectors are an aggregated of different NAICS activities which are unfortunately not explained in detial (gerade für die ist nix angegeben!!!)
  + 🡪 data needs to become better; also more standardized – i.e. practices in diff. countries (pointed at by different fits for different countries in EXIOBASE, e.g. good for China, very bad for UK; what is wring with construction flows in UK EXIOBASE?)
  + Try this with other data sources -GLORIA – specifically built for material footprints might adhere clsoer to material flow logic and provide better results. Additionally, distinguishing construction into buildings and civil engineering (this will be one of our next steps)
* Last but not least this might also point towards the limits of using monetary accounting data for physical purposed due to differing underlying system boundaries / objects of interest for reporting (e.g. for alu to soft drink sector in monetary units makes sense; in physical way there might better be another step involved?). In theory transaction specific prices could still change a lot, but also there data is scarce and without adequate pyhsical data to compare with, we cannot be sure that resulting end-use shares are correct
* The initial hope of obtaining very high end-use resolution with detailed MIOTs remains rather inconclusive
  + especially little physical data to compare with
  + we do know however that sector-level comparison prone to errort (CITE)
  + chen 2015/2017
  + for higher resolution end-uses, increasingly MIOT sectors might not be allocate to preferred dMFA end-use categories due to unclear end-use (e.g. ‘residential repairs’ unclear if to single- or multifamily housing)
  + Second, when getting to the medium and low-level sector aggregation, e.g. to single-family versus multi-family housing, another classification problem arises: categories as for instance ‘residential alterations and repairs’ (or similar, between 4-21% of cement use from 1963-2021, Figure 3) cannot unequivocally be allocated to either single or multi-family housing. The same issue already applies when leaving the highest aggregation level ‘construction’, which according to our aggregation matrix, also includes crude products such as ‘ready-mix concrete manufacturing’ that are reported to be delivered to final demand (e.g. for HT-WIO making up 6-8% of cement use in 2012): when disaggregating for instance from high-aggregation ‘construction’ to medium-aggregation (non-)residential and civil engineering, it is unclear to which parts the ‘read-mixed concrete’ enters the four categories (and thus the values derived for medium-level categories only include material use that is unambiguously associated and might therefore be underestimated). One option to avoid this is to delete the final demand of such crude products (as done for in original Ghosh-IO AMC). In that case this would raise the shares of other sector categories proportionally to their end-use shares. However, we would like to stay close to the original data and therefore did not apply this step.

Irgendwo noch unterbringen: choice of extension sectors and sector resolution, filter matrix design, interpretation of sector end-use

* + For the WIO-MFA/HT-WIO, the ‘materials’ sector in (equation 2) acts like a use-extension to the industry system (determines the distribution of materials to downstream industry sectors). Thus, the choice of ‘materials’ sector for the two methods is a crucial step which is restricted by the sectors available in the MIOT at hand (if not making efforts to further disaggregate/aggregate). When applying the end-use shares to a case study of material flows it is therefore important that the type of material flow (e.g. saw logs vs. veneer sheets) is assigned with the closes fit as allowed by MIOT sector resolution (e.g. when sawmills vs. veneer producers are distinguished; if only one crude wood sector no choice but to assign to this one)
  + Interpretation of functional use in sectors (e.g. alu in beverage sector = packaging)
    - Some transactions require the guessing of end-uses. For example in year X, Y% of direct shipments (Z matrix) flow from primary aluminum production to soft drinks manufacturing. As the aluminum is probably not part of the liquid for drinking itself one can only guess that it must be for packaging. In this case it is more or less straight forward. In other cases the guess might be more difficult
    - Although USA benchmark tables are one of the most detailed IOTs worldwide, sometimes resolution not sufficient. E.g. in NAICS journal 326199 All Other Plastics Product Manufacturing comprises different end-uses, e.g. floor coverings (construction), dinnerware (consumer durables), air mattresses (furniture) and plastic bottle caps and lids (packaging)

## Applying end-use shares to material flows for many countries and years via MRIOs?

* (match of MRIO data to national MIOT and shipment data)
* We saw that EXIOBASE in general worse than national data; end-uses very aggregated in EXIOBASE; no packaging sector
* Comparing EXIOBASE fit to available country-level shipments gives mixed picture (e.g. rather good fit for China and bad fit for UK)
  + 🡪 stuff that is used as extension more delivered to final demand in EXIOBASE 🡪 less material destinations can be identified
  + Extensions and end-uses much lower in resolution
  + 🡪 stuff that is used as extension more delivered to final demand in EXIOBASE 🡪 less material destinations can be identified
  + End-uses really aggregated; e.g. no packaging distinguished and if assuming that only food stuff is packaging, strongly underestimating packaging material use
  + Disaggregation of construction sectors
    - NAICS codes for construction are not explicitly stated
* Maybe all better for GLORIA

# Conclusions

* Conclusion on the application of end-use shares to economy-wide MFA

# Acknowledgements

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# Supplementary Information 1 (SI1)

## S1.1 Industry shipment data for countries other than USA

Table S1.1: Industry shipment data for other countries (sometimes including USA) and global. Some data sources are model outputs and no industry shipment data (see last column ‘comments’). For many data sources it is unclear whether end-use shares refer to apparent material consumption to final demand, or of shipments to manufacturing sectors (in the latter case, final product trade needs to be added).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Source | Scope | End-uses | Data from / comments |
| Aluminum | Liu and Müller (2013) | 20 countries, varying years (min. 1950, max. 2010) | Building & construction, transportation, containers & packaging, machinery & equipment, electrical engineering, consumer durables, others | various sources (see paper) |
| Ciacci et al. (2013) | Italy 2013 | Transportation, building and construction, machinery and equipment, consumer durables, electrical engineering, containers and packaging, other | Italian and European industry (associations) |
| Bertram et al. (2017) & IAI (2022) | 9 global regions, exact time and geographical scope unclear | Building & construction, transportation (auto & lt truck, aerospace, truck/bus/..), packaging (cans, other), machinery & equipment, electrical (cable, other), consumer durables, destructive uses, other | Various country and regional aluminum associations; time and space coverage unclear (see sources) |
| Cement | Cao et al. (2017b) | Global, 184 countries, min. ~1990, max. 2011 | Civil engineering, nonresidential buildings, residential buildings | Statistics by industry experts, e.g. PCA, Cembureau |
| Copper | Ciacci et al. (2017) | EU 28, two-yearly 1987-1995, 2008-2014 | Building and construction, electrical and electronic goods, industrial machinery and equipment, transportation equipment, consumer and general products | IWCC, personal communication with Soulier, M. (Fraunhofer ISI), Thomson Reuters GFMS |
| Glöser et al. (2013) | Global, 1912-2008 -2010 | Plumbing, building plant, architecture, communication, electrical power, power utility, telecommunication, (non-)electrical industrial, (non-)electrical automotive, other transportation, consumer products, cooling, electronic, powders (agriculture), diverse | ICSG, ICA & Ayres et al. (2003), resolution unclear |
| (IWCC 2017) (IWCC 2017) | Global, 2011-15 | - |
| Spatari et al. (2005) | North America, time coverage unclear | Building and Construction (on-site waste, plumbing, Wiring, built-in appliances), electrical and electronic equipment (industrial, consumer), infrastructure, transport equipment (motor vehicles, other Transport) | various, e.g. U.S. Bureau of Mines (1941), CDA (1980), literature, expert knowledge |
| Iron & steel  . | Pauliuk et al. (2012) assoc. data | China, 1998-2010 | Construction, transportation, machinery, appliances, other | Development Research Center of the State Council of China |
| Pauliuk et al. (2013) | India 1995-1999, UK 1960-65 & 1970-2000, USA 2004 | Construction, machinery products, transportation, other | USA: AISI (1941-2005), UK: ISSB (1979) & Dahlström et al. (2004), India: SERC |
| Hu et al. (2010) | China, 2004 | Urban residential buildings, rural residential buildings, non-residential buildings, non-construction | Development Research Center of the State Council of China |
| World Steel Association (2012) | Global, 2011 | Construction, mechanical machinery, metal products , automotive, other transport , electrical equipment, domestic appliances | - |
| Plastics | Geyer et al. (2017) | Global, static | Transportation, packaging, building and construction, electrical/electronic, consumer & institutional products, industrial machinery, others | Various, e.g. PlasticsEurope, ACC, CPMAI, for EU, USA, China, India for 2002-14 |
| Euromap (2016) | 63 countries/ regions 2009-15 | Packaging, automotive, construction industry, electrical/electronics & telecom, others | - |
| Plastics Europe (2006-2021) | EU-28\*NO/CH, 2006-2018 | Packaging, building and construction , automotive, electrical & electronic, agriculture, other | - |
| Jiang et al. (2020) | China, 1978, 1980-2015 (five-yearly), 2017 | Packaging, B&C, Automobile, Electronics, Agriculture, Other | No industry shipments but model output derived from various sector split data sources and bottom-up calculations |
| Mutha et al. (2006) | India, 2000 | Packaging, building and construction , consumer products , industrial goods , others | Southern Gujarat Chamber of Commerce and Industry (2000) |
| Zhang et al. (2007) | China, 2000 | Packaging, commodity , industry , agriculture, architecture | Liao and Liu (2000) |
| Glass | Pilkington 2010 | Global, 2009 (flat glass) |  |  |

\* For lead, zinc sources only report intermediate use categories; additionally several sources which do not necessarily draw on primary data from industry associations but rather on secondary literature (e.g. (Elshkaki et al. 2018; Graedel et al. 2015; Ciacci et al. 2015)

## S1.2 Details for calculation of MIOT and shipment-based end-use shares

### S.1.2.1 General preparation of monetary input-output tables (national USA, EXIOBASE)

For the years 1963/67 U.S. input-output data are published as industry-industry MIOTs. From 1972 onwards tables are published as supply-use tables following the commodity-industry approach (US BEA 2021). For the supply-use tables (SUTs) we followed the BEA’s approach to construct commodity-commodity MIOTs using an industry technology construct. Commodity-commodity tables appear superior to industry-industry tables, as the end-use shares refer to product-use not industries. That might also be the reason that also Chen and Graedel (2015) and Pauliuk et al. (2017) used commodity-commodity tables. For the years 1963 and 1967 we used tables as reported in industry-industry format.

Besides the construction of symmetric MIOTs, we modified original tables in two instances to prepare them for calculating end-use shares: First of all, the tables represent single-region accounts, i.e. they include imports in the intermediate demand matrix Z, as well as exports and changes in inventories as final demand accounts (as well as a final demand vector for imports as negative values). For the calculation of end-use shares we were interested in the domestic use within the USA, i.e. accounting for imports but not exports, which required to adjust MIOT system boundaries. Therefore we removed exports and the column of negative imports (meant to subtract imports) from final demand. We also removed changes to inventories, as we were only interested in use within the same year and do not want to model inventory changes. Second, some MIOTs/SUTs showed few and small negative transactions and empty (=zero) commodity output. While we accepted empty rows, we clipped negative values and replaced them by zero to ensure positive results. As negative values are few and small we expect the bias on results to be minor.

For the multi-regional MIOT (MRIO) EXIOBASE, we used product-product (commodity-commodity) tables and drew on the direct flow and final demand to calculate all required variables. As for the U.S. national tables, we removed exports and inventory changes from final demand.

### S.1.2.2 Choice of ‘extension’ sectors

For calculating the end-use share matrix , we did not use actual environmental extensions but just evaluate the monetary deliveries to final demand for selected ‘material sectors’ that we then assume to represent the shares of material-to-product allocations ( in Streeck et al. 2022, in constrast to ). We chose the respective ‘material sectors’ according to their label and description (for the USA in the NAICS (2017) manual) that closest match the properties of a potential extension, for example ‘iron & steel production’ as the material sector allocating the domestic use of crude steel material flows. From literature we know that the choice of ‘material sectors’ (or extensions) has strong influence on EEIO results (Owen et al. 2017; Wieland et al. 2020). For the detailed U.S. tables, several ‘material sectors’ potentially qualify as ‘extension’. Therefore, we calculated end-use shares for two sets of ‘material sectors’ and evaluate their influence on results (see SI1.3.1 for results). Table S1.2 depicts the two sets of ‘material sectors’.

Table S1.2: The two sets of ‘material sectors’ (sectors for matching environmental extensions) chosen for USA MIOTs.

|  |  |  |
| --- | --- | --- |
|  | Base scenario | Scenario with aggregated ‘material sectors’ (name: ‘extAgg’) |
| 2007/12 (difference for wood, steel, alu, paper, asphalt, plastic) | Sawmills and wood preservation; Clay product and refractory manufacturing; Glass and glass product manufacturing; Cement manufacturing; Cut stone and stone product manufacturing; Iron and steel mills and ferroalloy manufacturing; Alumina refining and primary aluminum production; Nonferrous Metal (except Aluminum) Smelting and Refining; Copper rolling, drawing, extruding and alloying; Pulp mills; Asphalt paving mixture and block manufacturing; Plastics material and resin manufacturing | Sawmills and wood preservation+Veneer, plywood, and engineered wood product manufacturing;  Clay product and refractory manufacturing; Glass and glass product manufacturing; Cement manufacturing; Cut stone and stone product manufacturing; Iron and steel mills and ferroalloy manufacturing+Steel product manufacturing from purchased steel; Alumina refining and primary aluminum production+Aluminum product manufacturing from purchased aluminum; Nonferrous Metal (except Aluminum) Smelting and Refining; Copper rolling, drawing, extruding and alloying  Paper mills+Paperboard mills; Asphalt paving mixture and block manufacturing+Asphalt shingle and coating materials manufacturing; Plastics material and resin manufacturing+Synthetic rubber and artificial and synthetic fibers and filaments manufacturing |
| 2002  (difference for wood, steel, alu, paper, asphalt, plastic) | Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying; Sawmills and wood preservation; Pulp mills; Asphalt paving mixture and block manufacturing; Plastics material and resin manufacturing; Brick, tile, and other structural clay product manufacturing; Flat glass manufacturing  Glass container manufacturing; Cement manufacturing; Cut stone and stone product manufacturing  Iron and steel mills and ferroalloy manufacturing; Alumina refining and primary aluminum production; Primary smelting and refining of copper; Primary smelting and refining of nonferrous metal (except copper and aluminum) | Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying; Sawmills and wood preservation+Veneer and plywood manufacturing; Paper mills+Paperboard mills; Asphalt paving mixture and block manufacturing+Asphalt shingle and coating materials manufacturing; Plastics material and resin manufacturing+Synthetic rubber manufacturing; Brick, tile, and other structural clay product manufacturing; Flat glass manufacturing; Glass container manufacturing; Cement manufacturing; Cut stone and stone product manufacturing; Iron and steel mills and ferroalloy manufacturing+Steel product manufacturing from purchased steel; Secondary smelting and alloying of aluminum+Alumina refining and primary aluminum production+Aluminum product manufacturing from purchased aluminum; Primary smelting and refining of copper; Primary smelting and refining of nonferrous metal (except copper and aluminum) |
| 1997 (difference for wood, asphalt, plastic) | Sand, gravel, clay, and refractory mining; Sawmills; Paper and paperboard mills; Asphalt paving mixture and block manufacturing; Asphalt shingle and coating materials manufacturing; Plastics material and resin manufacturing; Synthetic rubber manufacturing; Brick and structural clay tile manufacturing; Ceramic wall and floor tile manufacturing; Glass container manufacturing; Glass and glass products, except glass containers; Cement manufacturing; Cut stone and stone product manufacturing; Iron and steel mills; Primary aluminum production; Primary smelting and refining of copper; Primary nonferrous metal, except copper and aluminum | Sand, gravel, clay, and refractory mining; Sawmills+Veneer and plywood manufacturing; Paper and paperboard mills; Asphalt paving mixture and block manufacturing+Asphalt shingle and coating materials manufacturing; Plastics material and resin manufacturing+Synthetic rubber manufacturing; Brick and structural clay tile manufacturing; Ceramic wall and floor tile manufacturing; Glass container manufacturing; Glass and glass products, except glass containers; Cement manufacturing; Cut stone and stone product manufacturing; Iron and steel mills; Primary aluminum production; Primary smelting and refining of copper; Primary nonferrous metal, except copper and aluminum |
| 1992/1987  (difference for wood, asphalt, plastic) | Sand and gravel; Sawmills and planing mills, general; Paper and paperboard mills; Plastics materials and resins; Synthetic rubber; Asphalt paving mixtures and blocks; Asphalt felts and coatings; Glass and glass products, except containers; Glass containers; Cement, hydraulic; Brick and structural clay tile; Ceramic wall and floor tile; Cut stone and stone products; Blast furnaces and steel mills; Primary smelting and refining of copper; Primary aluminum; Primary nonferrous metals, n.e.c. | Sand and gravel; Sawmills and planing mills, general+Veneer and plywood; Paper and paperboard mills; Plastics materials and resins+Synthetic rubber; Asphalt paving mixtures and blocks+Asphalt felts and coatings; Glass and glass products, except containers; Glass containers; Cement, hydraulic  Brick and structural clay tile; Ceramic wall and floor tile; Cut stone and stone products; Blast furnaces and steel mills; Primary smelting and refining of copper; Primary aluminum; Primary nonferrous metals, n.e.c. |
| 1982-1967  (difference for wood, paper asphalt, plastic) | Sand and gravel mining; Sawmills and planing mills, general; Pulp mills; Plastics materials and resins  Synthetic rubber; Paving mixtures and blocks; Asphalt felts and coatings; Glass and glass products, except containers; Glass containers; Cement, hydraulic; Brick and structural clay tile; Ceramic wall and floor tile; Cut stone and stone products; Blast furnaces and steel mills; Primary copper; Primary lead; Primary zinc; Primary aluminum and alumina; Primary nonferrous metals, n.e.c. | Sand and gravel mining; Sawmills and planing mills, general+Veneer and plywood; Paper mills, except building paper+Paperboard mills+Building paper and board mills; Plastics materials and resins+Synthetic rubber; Paving mixtures and blocks+Asphalt felts and coatings; Glass and glass products, except containers; Glass containers; Cement, hydraulic; Brick and structural clay tile; Ceramic wall and floor tile; Cut stone and stone products; Blast furnaces and steel mills; Primary copper; Primary lead; Primary zinc; Primary aluminum and alumina; Primary nonferrous metals, n.e.c. |
| 1963 (difference for wood, paper asphalt, plastic) | Sawmills & planning mills, general; Pulp mills; Plastics materials & resins; Synthetic rubber; Paving mixtures & blocks; Asphalt felts & coatings; Glass & glass products except containers; Glass containers; Cement, hydraulic; Brick & structural clay tile; Ceramic wall & floor tile; Cut stone & stone products; Blast furnace & basic steel products; Primary copper; Primary lead; Primary zinc; Primary aluminum; Primary nonferrous metals, nec. | Sawmills & planning mills, general+Veneer & plywood; Paper mills, except building paper+Paperboard mills+Wallpaper & building paper & board mills; Plastics materials & resins+Synthetic rubber; Paving mixtures & blocks+Asphalt felts & coatings; Glass & glass products except containers; Glass containers; Cement, hydraulic; Brick & structural clay tile; Ceramic wall & floor tile; Cut stone & stone products; Blast furnace & basic steel products; Primary copper; Primary lead; Primary zinc; Primary aluminum; Primary nonferrous metals, nec. |

### S.1.2.3 Filter matrices

As described in section 2.3, all MIOT-based methods except for CBA required the definition of filter matrices. We here give the detailed rationale, as well as configuration of chosen filters.

For **WIO-MFA**, two types of filter matrices need to be designed: the mass filter and the yield filter. The mass filter removes monetary transactions/flows that are believed to have no physical counterpart, such as service flows (see Table 2). The unequivocal classification of transactions as ‘non-physical’ requires detailed knowledge of the MIOTs’ only known by national statistic bureaus, the decisions of practitioners thus often remaining subjective to some degree (also see Steeck et al. 2022). Here we construct two scenarios in order to make the effect of these decisions somewhat transparent. First of all, we classified MIOT sectors as either raw materials, materials, products, or services (see Data SI). Then, depending on the scenario, the output and/or input of the raw material and service products was filtered, i.e. set to zero (Table 5).

In addition to the mass filter, the yield filter removes a share of MIOT transactions in order to account for physical waste flows that occur during each supply-chain step. The compilation of yield filter for high-resolution MIOTs takes considerable effort and to our knowledge none of these filters are published. In this work we apply detailed yield filter for the transactions associated to the materials aluminum, copper, iron and steel and simplified filters for other materials to EXIOBASE MIOTs (see Appendix X for waste filter). The compilation of detailed yield filter for the high-resolution USA MIOTs is not within scope of this work. In a first approximation, we use the yields obtained for EXIOBASE also for USA MIOTs.

For the Ghosh-IO AMC filters were designed according to Duchin and Levine (2010): no mass or yield filters were applied but reverse transactions from products to materials were prohibited (by partitioning of Q in equation 6 in main manuscript) and the final demand of sectors selected as ‘materials’ were set to zero.

For the **Partial Ghosh-IO** filter, products have to be differentiated into intermediate and end-use products. Aryapratama and Pauliuk (2019) evaluate the differentiation in their case study according to the ratio between the value of product output going to intermediate versus final demand. Following this reasoning, a product with high output ratio to intermediate demand and low ratio to final demand is classified as intermediate product, while in the reverse case as end-use. In our calculations we followed that approach with a slightly different reasoning.: At a ratio of intermediate divided by final demand equal or above a value of 1.1 (rounded) we classified the respective product as intermediate, except if the product could unambiguously be identified as an end-use in the sense of our work by its label (e.g. product label ‘bicycle’). In that case, all material delivered to this commodity would be classified as end-use according to product label. We marked these items yellow in the filter matrices (see Data SI; mostly the case for packaging, maintenance of buildings and structures, a few single items of furniture or electronics and all food items). For example, in the U.S. MIOT for the year 2012, the ratio of Z/Y of ‘Metal can, box, and other metal container (light gauge) manufacturing’ is 45 because these containers are considered an intermediate input to other products. For the purpose of material end-uses in dMFA however, we identify the product as end-use and not intermediate use by its label and therefore classify it accordingly. In order to avoid downstream shipments to service sectors (see section 3.4 ‘Calculations to bridge the logic between IOA and MFA’) we accounted for intermediate demand only for those sectors not classified as ‘services’ according to our filter matrix. We calculated ratios after removing any negatives from Z and Y.

Arguably the ratio of intermediate to final demand we chose is arbitrary to some degree, which reflects the general sensitivity of the Partial Ghosh-IO AMC approach to practitioner decisions. As mentioned in Streeck et al. 2022, the Partial Ghosh-IO AMC might lead to misclassification as once classified as intermediate product, the incorporation into other end-use products does not occur (e.g. air ventilation going to a car classified as air ventilation instead of car). Also sectors that only receive inputs but are not considered to distribute further downstream were classified as end-use (e.g. agricultural sectors).

### S.1.2.4 Yield correciton for industry shipments

We applied yield corrections to industry shipments in physical units for aluminum and wood (see Excel Sheet on GitHub). For iron and steel, cement, copper and plastics we did not apply any yield corrections for the following reasons:

* Iron & Steel: USGS data exhibits high volumes of material shipped to service centers and categories for which end-use cannot be identified (e.g. ‘others’); for YSTAFB it was unclear whether yield correction has already been applied in published data
* Cement: no data and yields per application expected to be very similar
* Copper: no yield correction applied because all yields in WIO-MFA yield matrix were ~1
* Plastics: yield for the largest end-use ‘packaging’ missing

### S.1.2.4 Aggregation matrices for USA

The sector categories of U.S. MIOTs changed over time, so that slight inconsistency of product-to-sector allocation may occur in the time series. In some tables, for instance, products were very detailed and could be assigned to different end-uses (n productst0 : n sectorst0), while in others aggregated to one product group that was allocated to one end-use (n productst0 = 1 productt1 : 1 sectort0/1). Also, in early tables some product labels were missing, in which case the product was allocated to the end-use that neighboring products referred to.

## S.1.3 Additional results and result details

### S.1.3.1 Details of different MIOT method comparison

More details regarding the claims in 3.1.2:

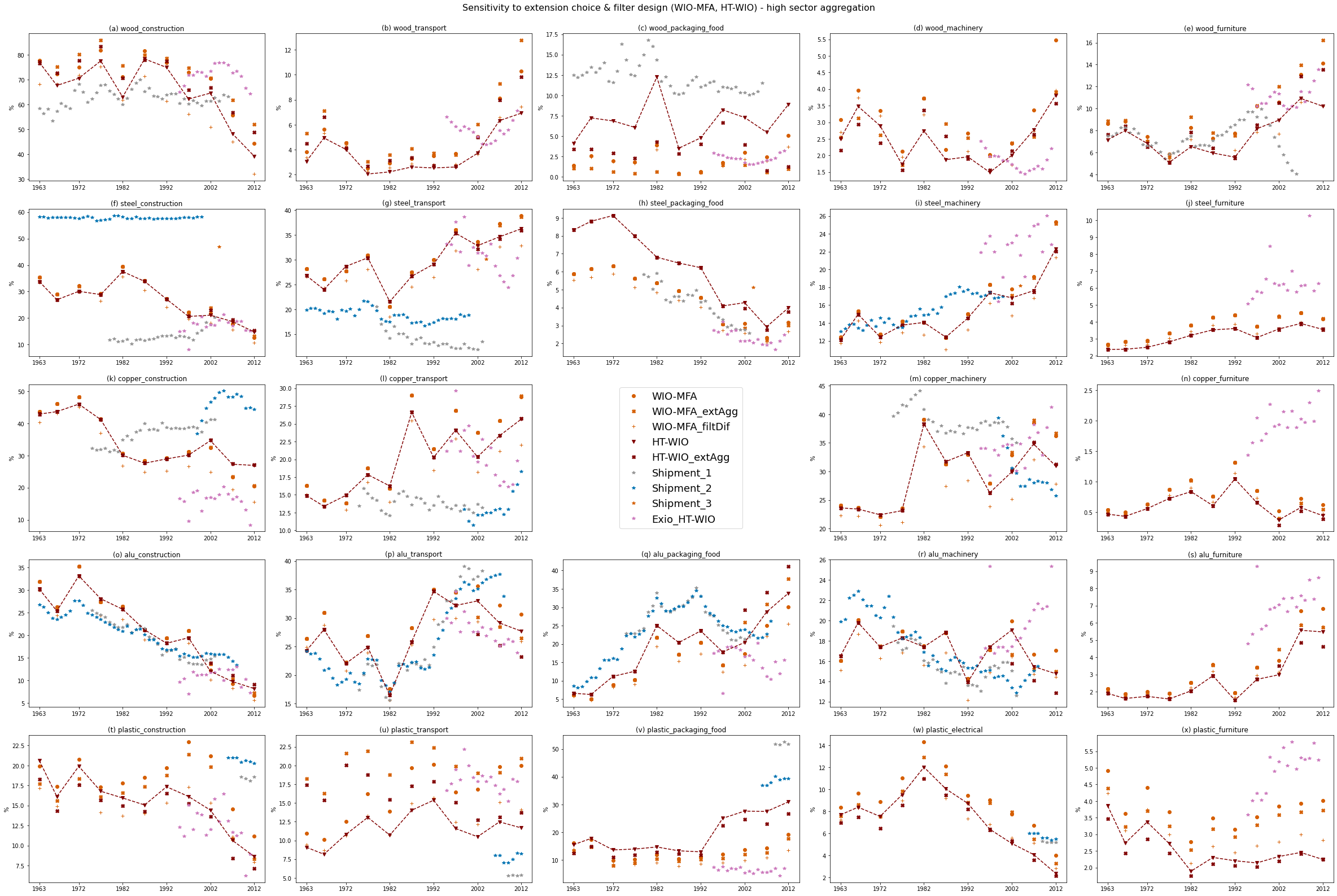
* As explained in 3.1.2, the difference between HT-WIO and other methods would be more pronounced, if we did not interprete the use of above materials delivered to ‘food products’ as ‘packaging’ too. Although this step must be regarded as personal interpretation, we took it as for aluminum and glass large parts of materials are directly delivered from the ‘material’ sectors to these food products (e.g. in 2012 direct flow matrix, 9% of ‘Alumina refining and primary aluminum production’ going to ‘Soft drink and ice manufacturing’ via one crude material manufacturing supply chain step). In that particular case we argue that the interpretation as material being packaging is justified (as it is likely that the large amounts of aluminum and glass going to the beverage industry end up as packaging). Of course it would be preferable if these transactions would be accounted as packaging in the first place.
* For plastics, the cutting difference in plot Figure 2 (v) for ‘plastics packaging’ in 1997 can be explained by plastic packaging and bottle sectors before 1997 not being discerned as separate sector in U.S. MIOTs. These sectors could thus not be subject to the ‘Hypothetical Transfer’ in HT-WIO or be defined as end-use in partial Ghosh-IO.
* For wood, the large differences between HT-WIO and other methods can be explained by large parts of the direct packaging deliveries (intermediate demand Z as share of total output x) going to the service sectors (e.g. 1987: 81% of ‘Wood pallets and skids’ going to services, specifically 77% to ‘Wholesale trade’; for ‘Wood containers, n.e.c.’ 22% go to services; vs. e.g. only 6% of ‘Metal cans’ and 15% of ‘Metal shipping barrels, drums, kegs, and pails’ going to service sectors). As indicated in Figure 1, we transferred deliveries (=inputs) to service sectors to final demand during Hypothetical Transfer, which then rises wood packaging end-use shares.
* For categories others than packaging, the WIO-MFA vs. HT-WIO difference can be explained by HT-WIO indirectly changing the end-use shares of categories other than packaging: because larger amounts of materials are allocated to packaging and other intermediate products (inputs to service sectors) that are end-use in dMFA sense, relatively less material is allocated to other end-uses.
* The results of CBA and Ghosh-IO AMC align closely, because in the current configuration both of them calculate embodied materials. Despite the difference in underlying IO-models, the application of those to at scale MIOTs produces equivalent results if data is not manipulated otherwise (see Streeck et al. 2022). In our application, the only difference between the two methods is that in Ghosh-IO AMC positions materials external to the industry supply chain (partitioning of matrix, see eq. 6) and deliveries to final demand are deleted (see Streeck et al 2022).

### S.1.3.2 Sensitivity of MIOT-based end-use shares to ‘extension’ sector & filter matrix choices

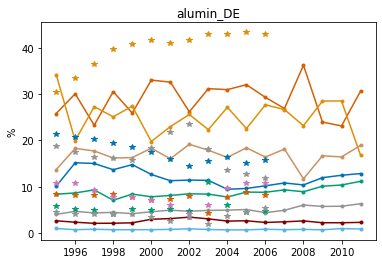
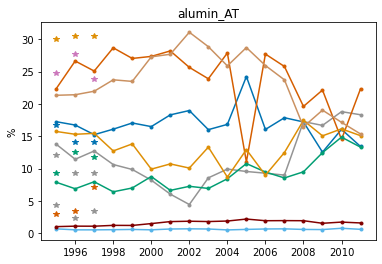
Table 3: Scenarios for evaluating the sensitivity of end-use shares derived via WIO-MFA for the USA monetary input-output tables to modifying (A) sectors considered as ‘material extensions’ (B) no modification, (C) deleting inputs to raw material and service sectors (for definition of these sectors read on and see mass filter matrices in Data SI), and (D) system boundary changes = hypothetical transfer of monetary interindustry transactions to final demand / value added.

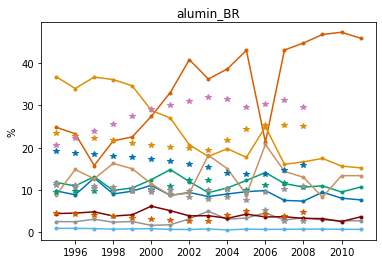
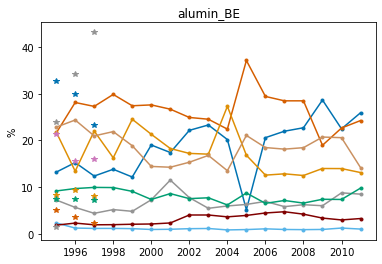
|  |  |  |
| --- | --- | --- |
| **Sensitivity to** | **Scenario label** | **Description** |
| Base | WIO-MFA (plain) | Products do not become part of materials; deletion of output of service sectors (non-physical flows); correction for waste flows via yield filters; technological coefficients in **A** matrix deleted for inputs (columns) to raw material and service sectors deleted |
| Deletion of sector inputs | WIO-MFA: inputs to raw material and services kept | Technological coefficients in **A** matrix kept for inputs (columns) to raw material and service sectors deleted |
| Variation of ‘material extension sectors’ | WIO-MFA / HT-WIO: extension variation | Extension modified by aggregation of two to three sectors as extension or switching of extension sector (adopting configuration of scenario C – Hypothetical Transfer) |

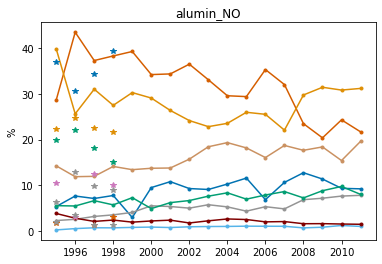
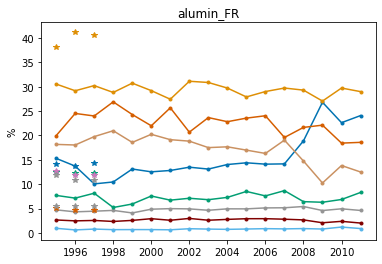
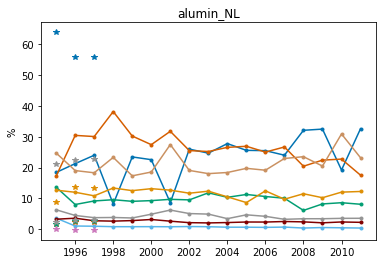
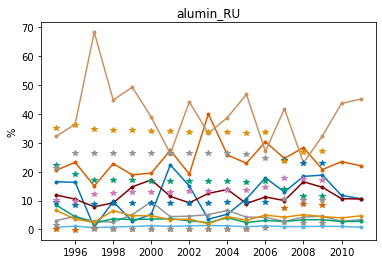
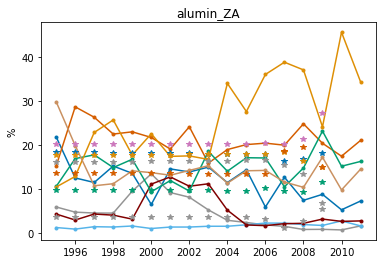
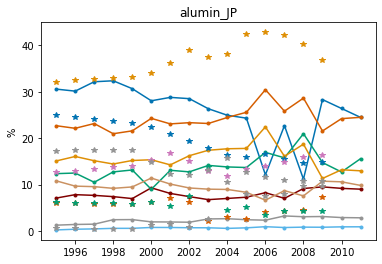
* We show results for WIO-MFA and HT-WIO as the two most promising methods (see Streeck et al 2022, and section 2.2). Additionally, we show variations of these methods:
* First, the sensitivity to the WIO-MFA mass filter that delete monetary transactions assumed to contain no physical counterpart, and second, the sensitivity to choice of the MIOT sectors that are assumed to distribute materials to the supply chain according to MIOT transaction values, or more specifically the shares of the material sectors output to other industry sectors (e.g. crude steel assumed to be distributed by sector ‘steel mills’)
* For WIO-MFA mass filters, we ran two scenarios: the base case, where inputs and outputs to service sectors are deleted (termed ‘WIO-MFA’ in Figure 4), and one keeping these (‘WIO-MFA\_filtDif’). For the choice of ‘material sectors’, we ran two scenarios as well: the base case, in which one sector of the original MIOT resolution is chosen to introduce materials (‘HT-WIO’), and one, where we aggregated two or three sectors for materials where that seemed appropriate (‘HT-WIO\_extAgg’), thereby merging the output structure of these sectors (for merged sectors see Table 6)
* For the WIO-MFA mass filter scenarios, we find deviations of mean X% (median Y%, max Z%, min A%). What is striking is that results ‘WIO-MFA\_filtDif’ are lower than ‘WIO-MFA’ in all instances. This can be explained by higher end-use shares of the ‘service sectors’ which result in lower shares for all other end-uses. To determine end-uses, we actually want to avoid this case, as the purpose in the sense of product stocks is unclear for service sectors (or subjective judgement needs to be applied when for instance determining the end-use of steel deliveries to ‘hotels and restaurants’ services). However, as argued in 2.3 section ‘Filter matrices’ we suggest that just deleting the inputs to service sectors biases results as the ‘upstream pull-effect’ of service demand is deleted (outputs in turn can and should be deleted as these most probably do not correspond to physical flows). As a solution, we suggest the applied HT-WIO which transfers the product inputs to service sectors to final demand, which the can be identified as end-use product stocks and incorporate the service demand pull-effect.
* Looking at the materials for which sectors were aggregated for all years (wood, plastics; Table 6), we find slight to strong deviation, depending on end-use. Relative deviation for both HT-WIO scenarios overall was mean X% (median Y%, max Z%, min A%), with strongest deviation for XXXX
* We already know from literature and results, that choice of the MIOT sector that is assumed to distribute materials can strongly affect results (Owen, Wieland), which is in turn illustrate by our results (e.g. Figure 4i plastic in transport). For the WIO-MFA/HT-WIO, the ‘materials’ sector in (equation 2) acts like a use-extension to the industry system (determines the distribution of materials to downstream industry sectors). Thus, the choice of ‘materials’ sector for the two methods is a crucial step which is restricted by the sectors available in the MIOT at hand (if not making efforts to further disaggregate/aggregate). When applying the end-use shares to a case study of material flows it is therefore important that the type of material flow (e.g. saw logs vs. veneer sheets) is assigned with the closes fit as allowed by MIOT sector resolution (e.g. when sawmills vs. veneer producers are distinguished; if only one crude wood sector no choice but to assign to this one)
* For WIO-MFA mass filters, we find deviations of mean X% (median Y%, max Z%, min A%). What is striking is that results ‘WIO-MFA\_filtDif’ for all end-uses except ‘services’ are lower than for ‘WIO-MFA’ in all instances. This can be explained by higher end-use shares of the ‘service sectors’ in ‘WIO-MFA\_filtDif’ which results in lower shares for all other end-uses.

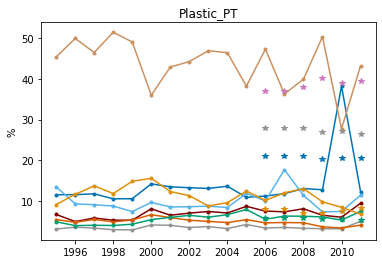
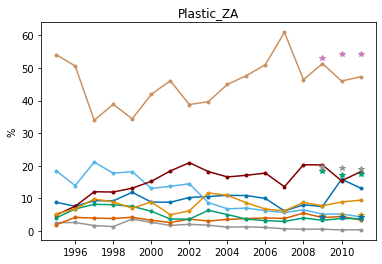
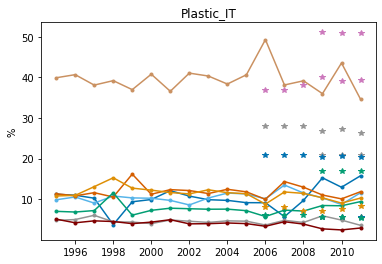
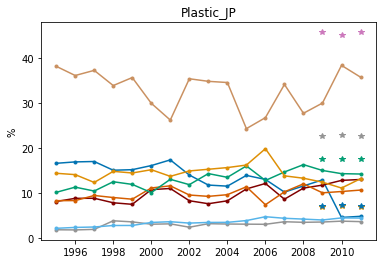
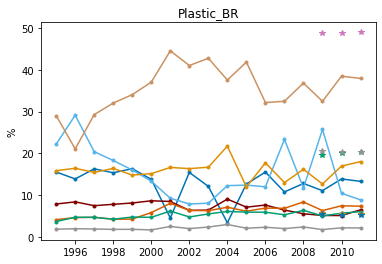
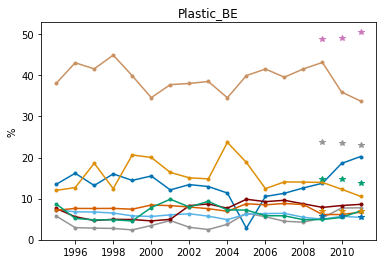
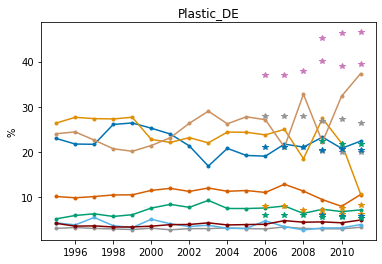
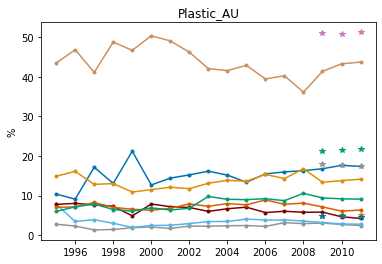
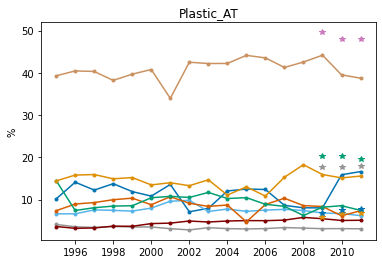
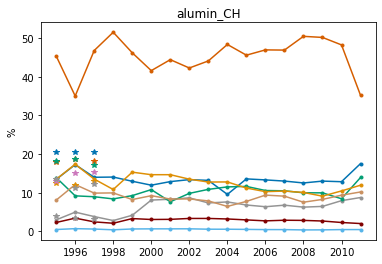


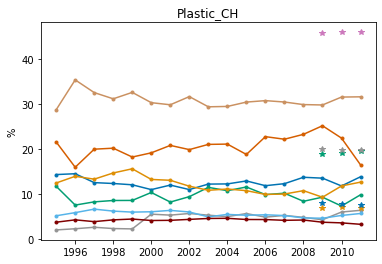
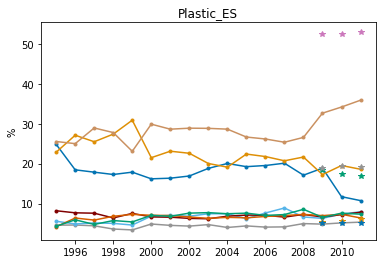
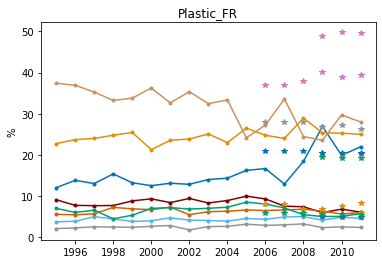
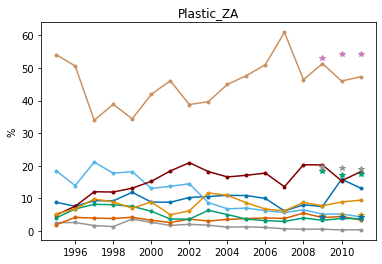
### S.1.3.3 Additional result plots EXIOBASE (MIOT-based results for HT-WIO)













# Supplementary information 2 (SI2)



# Data SI 1

# Potential Additional Analysis

* Compare tin industry shipments from USGS for the USA with MIOT-based results for EXIOBASE (national official US MIOTs don’t have ‘tin’ sector)
* Clean up the shipment Excel for GitHub
* Compare results also to GAS 20122 from Glenn
* Cao 2017 cement: Building (without s); not entirely clear if that means buildings or all (non)residential structures (also not from paper)
  + (does for instance the absent ‘s’ for Cao et al ‘building’ signify that categories refer to e.g. the residential construction (=building) industry, or do authors actually mean physical buildings as in houses)
* from USGS documentation (use to show system boundaries of shipments)
  + Data Source: The source of data for the iron and steel end-use worksheet is the American Iron and Steel Institute annual statistical report. Data are published in the iron and steel chapter of the Minerals Yearbook, an annual collection, compilation, and analysis of mineral industry data, published by the U.S. Bureau of Mines and the U.S. Geological Survey.
  + End Use: End use is defined as the use of the mineral commodity in a particular industrial sector or product. For iron and steel products, the end-use distribution is based on shipments of steel mill products. The end-use categories are service centers and distributors; construction; transportation (predominantly for automotive production); containers; and other industrial uses. The undistributed category accounts for net imports, minus imports of semifinished steel products plus/minus adjustment for stock changes for which iron and steel applications are unknown.
* Grafik für Asphalt 🡪 und mal an Dominik schicken
* In that regard discuss another way to use the MIOTs: only distribute national production and intermediate products via end-use shares and add net trade of final products according to end-use category thereafter. Discuss that here, or in companion paper/part II? Imports in final demand: the requirements are estimated using the domestic technology assumption. In theory it would thus be better to subtract net-imports from MIOT final demand and add these later via physical data. In practice however, we do not have information as to the exact imports of final demand for the USA national tables (BEA X) which makes it difficult to subtract them from aggregate final demand. Therefore we accept the domestic technology bias for the USA which produces a wide range of products. In EXIOBASE in contrast, where imported final demand is known, one can use the proper method.

Publication bibliography

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1. An example for a case in which services are involved is for instance, when ‘aluminum in air crafts’ are intermediate input to the service sector ‘government defense’. Accordingly, before delivery to final demand the ‘aluminum in air crafts’ is classified as the end-use ‘aluminum in government defense’. Thereby, the actual physical end-use in a MFA-sense (‘air crafts’) is lost. One might argue that ‘air crafts’ should not be intermediate input to other sectors following SNA (United Nations 2009) in the first place, but entirely delivered to final demand; however this is not always the case as several instances in the national U.S. benchmark MIOTs show (US BEA 2021); e.g. for 2007/12 use tables 14-15% of total commodity output of the sector ‘Aircraft manufacturing’ is reported to be delivered to the interindustry sector ‘Federal general government (defense)’. [↑](#footnote-ref-1)