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

Jan Streeck1,\*, Hanspeter Wieland1,2, Stefan Pauliuk3, Barbara Plank1, Kenichi Nakajima4, Dominik Wiedenhofer1

1 University of Natural Resources and Life Sciences, Vienna, Department for Economics and Social Sciences, Institute of Social Ecology, Schottenfeldgasse 29, 1070 Vienna, Austria

2 Vienna University of Economics and Business, Institute for Ecological Economics, Vienna, Austria

3Industrial Ecology Freiburg, Albert-Ludwigs University Freiburg, Freiburg (Germany)

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\*Corresponding author: [jan.streeck@boku.ac.at](mailto:jan.streeck@boku.ac.at)

# Abstract (long for now)

Several economy-wide dynamic Material Flow Analysis (dMFA) studies extrapolate fragmented information on material end-use products, i.e. the product stocks as which material consumption accumulates, for single countries and years across longer time periods and global countries. However, correct representation of end-uses is crucial to adequately model 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 assessments.

In part I of this work we reviewed and systematized five distinct approaches that derive information on end-use products via so-called ‘end-use shares’, i.e. ratios that split total material consumption to different end-uses, by drawing 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, and to the Multi-Regional Input-Output Model EXIOBASE. Additionally, we propose and apply methodological improvements for re-defining certain intermediate outputs as final demand in order to match MIOT-dMFA system boundaries for correct classification of material end-uses (‘Hypothetical Transfer’).

We find mixed results regarding the fit of end-use shares derived from industry shipments in physical and MIOTs-based results. For U.S. national data, some materials show rather good fit (e.g. aluminum with a relative median deviation 17%), while others deviate strongly (e.g. iron & steel relative median deviation is 46% with a maximum >200%). In many cases, the temporal trajectory of MIOT-based end-use shares approximated that of industry shipments, if also at different magnitude. For EXIOBASE, we found good fit for some countries and materials (e.g. steel and aluminum in China), while substantial under or overestimations for other countries can be observed (e.g. construction in UK). Aluminum in machinery seems to be systematically overestimated with EXIOBASE (sample of 14 countries). When interpreting these comparisons, one should keep in mind that also industry shipment data can come with many limitations, although when system boundaries are clear it still represents the data source closest to dMFA.

For the USA, Hypothetical Transfer in combination with WIO-MFA provides the best results for the end-use ‘packaging’, which otherwise is allocated as materials into other categories. EXIOBASE is problematic for evaluating end-use shares for materials for which ‘packaging’ is an important end-use, as its low resolution does not distinguish this sector.

To apply MIOT-based end-use shares to dMFA, without any idea of physical realities seems risky. However, together with available industry shipments, auxiliary country-level data (e.g. construction activity statistics) and qualitative data (e.g. preferred building types in countries), MIOT-based end-use shares might add information regarding temporal trajectory and variance between countries. Hopes are that new developments in MRIOs that are specifically build for material flows such as GLORIA provide better suited information for evaluating material end-uses.

# 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 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 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 requires huge efforts to achieve economy-wide coverage, if at all feasible due to data constraints. The ‘Resource Efficiency – Climate Change’ (RECC) model, for instance, represents material use in buildings and passenger vehicles with high level of detail regarding different material qualities and multiple 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 are inflow-driven ‘top-down’ dMFA approaches 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 the ‘bottom-up’ models is hardly achievable via the ‘top-down’ dMFA methodology, studies that introduce mid-level end-use detail to the latter exist (Streeck et al., in preparation). Examples are Dahlström et al. (2004), who introduce 6-9 end-use sectors to economy-wide material flows for crude iron, steel and aluminum in the UK, or Cao et al. (2017b) who introduce three end-use sectors for economy-wide cement use in 184 countries.

To model end-use detail, many of these studies use ‘*end-use shares’*, i.e. shares to split total material consumption to different end-use products or sectors (see Figure 1 in Streeck et al., in preparation). These end-use shares can be derived from two different data sources: first, data on industry shipments of materials to different manufacturing sectors 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 (applications in for example 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 (e.g. UNEP 2016), could quantify the material consumption in different end-use products or sectors at novel material and country resolution.

Therefore in Streeck et al. (in preparation) we reviewed the literature that used industry shipments and MIOTs to generate end-use shares and theoretically assessed five different approaches for their similarities, strengths and weaknesses. We concluded that the Waste Input-Output approach to MFA (WIO-MFA; Nakamura et al. 2007) represents the most accurate choice to derive end-use shares from MIOTs, as it closely sticks to the mass-balance principle of dMFA. However, also for WIO-MFA limitations remain regarding the match of MIOT-dMFA system boundaries (see Streeck et al. (in preparation) and section 2.1.1 in this paper for details). Furthermore, despite being inferior from a theoretical point of view, some approaches other than WIO-MFA might still be attractive for initial assessments due to their time-efficient application.

Here we apply the five identified approaches to derive end-use shares for empirical data, suggest one particular methodological improvement (‘Hypothetical Transfer’), and compare derived results between methods, materials and end-uses. We deploy the methods to U.S. MIOTs in a detailed comparison drawing on official national data with detailed product group resolution. Additionally, we apply an improved version of WIO-MFA (‘Hypothetical Transfer-WIO’) to the regions of the MRIO EXIOBASE (Stadler et al. 2018). 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 economy-wide Material Flow Accounting / Analysis?

# 2. Methodology

## 2.1 Summary of applied methods

In Streeck et al. (in preparation) 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 literature sources for deriving end-use shares from industry shipments in physical units (eq. 1) and the five input-output approaches (eqs. 2-12) used in this study. For a detailed description of methods, please refer to Streeck et al. (in preparation).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 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; to be combined with WIO-MFA, CBA or Ghosh-IO AMC to derive |
|  | (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 manufacturing sectors or markets from which end-uses can then be inferred and assumed according to sector / market label (e.g. ‘construction’). Industry shipments often only cover parts of total material consumption (see Streeck et al., in preparation for detailed explanation). For that reason, many of the studies identified in Streeck et al. (in preparation) 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., in preparation). For all models presented here, proportionality between monetary and physical flows is assumed as 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. 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 (eq. 5). 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., in preparation). 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; eq. 8). For detailed conduct of methods please refer to part I of this publication (Streeck et al., in preparation).

Of all described MIOT-based methods, WIO-MFA adheres most closely to the dMFA logic and can be regarded as most accurate for evaluating end-use shares from a theoretical point of view (Streeck et al., in preparation). However, as discussed in Streeck et al. (in preparation), 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: 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., in preparation). For instance, products such as ‘packaging’ are end-uses (= final demand) in the sense of dMFA but are classified as intermediate demand in MIOTs, meaning that they have zero or very small final demand themselves, but instead are delivered to other industries and incorporated in their output. 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. However, when calculating the common supply-chain tracing via Ghosh/Leontief inverse, these specific intermediate products (e.g. ‘plastics in packaging’) delivered to products for final demand (e.g. ‘motor vehicles’) are misclassified according to the end-use of the final product (e.g. 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’ might then for instance end up in the end-use ‘hotels and restaurants’, the physical use of which could only be guessed (might be packaging, but also other end-uses if these are accounted for as intermediate demand).[[1]](#footnote-1)

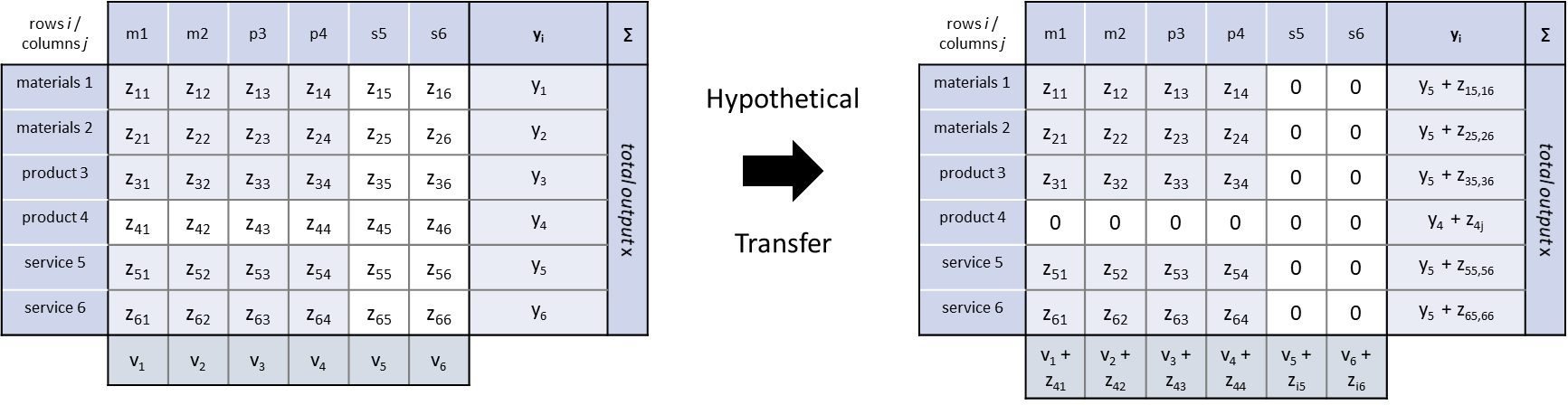
There are three ways to resolve end-use misclassification as ‘services’, while only one for assignment to the wrong ‘product’: 1) for ‘services’ one can ‘guess’ the end-use by assuming for instance that ‘plastics’ delivered to ‘hotels and restaurants’ end up as food packaging (e.g. similarly done for cement in Cao et al. 2017a), 2) one can simply delete the transactions to ‘services’ sectors which might seem intuitive for WIO-MFA mass filters (to our knowledge, no study reports steps from original to mass-filtered MIOTs so that dealing with ‘services’ in other studies 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 ‘services’ sectors’ final demand is neglected. Thus only case 3) seems sensible 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 sectors of detailed MIOTs such as the national U.S. official national MIOTs.

Therefore, we here propose a simple approach that corrects for misclassifications by transferring direct flows of particular transactions to final demand, and term that method ‘Hypothetical Transfer’(HT): the total flow matrix is used to transfer the transactions considered intermediate for MIOTs but end-use for dMFA (e.g. the total output of ‘packaging’ by MIOT sector) to final demand (Figure 1, Table 1 eqs. 11-12). This way the intermediate products of interest which formerly were endogenous to the interindustry system are exogenized to final demand, thereby keeping their end-use meaning 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 changing 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 ).

Hypothetical Transfer can be conducted for any full IO-model (considering both interindustry and final demand accounts). 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 (eqs. 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 MIOTs but end-use (final demand) in dynamic Material Flow Analysis (here: product 3), as well as monetary flows that most probably correspond to a physical counterpart but are input to services sectors (sector output to s5/s6), 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. (in preparation). 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

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 multi-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 materials USGS industry shipments only report intermediate use 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 fee-based

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 1.2.5); and where indicated in Table 2, material contained in final goods trade was added from data obtained in Streeck et al. (2021).

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 data we found distinguished between 5-10 end-use categories, and highest geographical resolution were 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), North America and EU28 for copper (Spatari et al. 2005; Ciacci et al. 2017), China, India, UK and USA for iron and steel (Dahlström et al. 2004; Pauliuk et al. 2012, 2013), ca. 63 countries for 2009-15 and longer for China and EU for plastics (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 detailed 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 as indicated in Table 2: 1) when shipments did not include trade in final products 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 S 1.2.4 and GitHub repository). 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 consumption, 2) how to identify the sectors that distribute materials to end-use, and the end-use meaning from sector labels, 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 (‘material sectors’) 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 qualified 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 therefore 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’ or ‘non-residential structures’ but could not unambiguously allocated to one of the latter according to their label and were thus classified under the category ‘other buildings’.
3. All MIOT-based approaches to calculate end-use shares require the definition of filter matrices (except for CBA). 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 filter 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 the 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 details on filter matrices please refer to SI 1.2.3.

# 3. Results

## 3.1 USA

Results in this section 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



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 14 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 . 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)

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 we aggregated for comparison, or categories such as ‘other’. For additional results please see SI 1.3 and GitHub repository.

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

In Figure 2, we compare the end-use shares for different materials, end-use categories and the U.S. national MIOTs, as well as EXIOBASE, to available industry shipments. We highlight ‘HT-WIO’ as the theoretically most accurate MIOT-based approach to trace material flows to end-use products (see section 2.1.1). 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). In text, we additionally describe the deviation over more than one subplot as the . Please note that the 5 selected end-uses in Figure 2 represent the lion’s share of material use but might not sum up to 100% due to remaining ‘other’ uses (see Data SI ‘HTWIO\_fullResults\_USA’ for overview of 100% allocation).

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: per material, the HT-WIO results for aluminum showed the best (relative deviation ,) while steel showed the worst fit to industry shipments (). The poor match for steel was 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 were 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 found 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 in subplots approximated 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 were 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 via differing definitions of absorbing states, mass filters and yield correction (section 2.1 & Streeck et al., in preparation). 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 performed surprisingly well, when comparing to HT-WIO results. For many materials and end-uses, these methods were 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 could be observed in particular for the end-use ‘packaging/food’. Here, the MIOT system boundary problem outlined in section 2.1.1 can be observed in action. Packaging is an ‘intermediate product’ in MIOTs, while an ‘end-use product’ in the sense of dMFA. The method ‘HT-WIO’ has been introduced to tackle this issue, while other methods that do not consider this problem performed 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 could 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 interpret the use of above materials in ‘food products’ as ‘packaging’ too (indicated by label [material]\_packaging\_food; e.g. ‘food products’ for aluminum made up 5-30%-points of aluminum in this category for 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 were 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 of one end-use change that means that shares of all others 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 varied 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 occurred for certain years or periods of latter panels. Partially, opposite trends and large outliers could be observed (e.g. panel (l): outlier in 1997 and large deviations since 2005). EXIOBASE performance was 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 was an exception as the lacking packaging sectors is compensated by considering deliveries to ‘food products’ 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 emerged. 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 no clear systematic, except for overestimation of ‘furniture’ end-use shares and underestimation 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 achieve very high end-use resolution corresponding to the MIOT sector resolution (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-level detail (‘civil engineering’, ‘residential’ and ‘nonresidential structures’), and high-level 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.[[2]](#footnote-2) Two things are important when interpreting Figure 3 results:

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 well 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’ resulted for the construction categories (e.g. ‘single- and multi-family structures’ in 2007/12: 15-35% of ‘paving mixtures’ end-use; ‘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 assumed categories such as ‘ready-mix concrete manufacturing’ (6-8% of 2012 cement use) or ‘residential alterations and repairs’ (between 4-21% of cement use from 1963-2021, Figure 3) to contribute. However, at higher resolution, we could not allocate ready-mix 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 found good fit of MIOT-based shares 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’ (panels b-c), we found 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

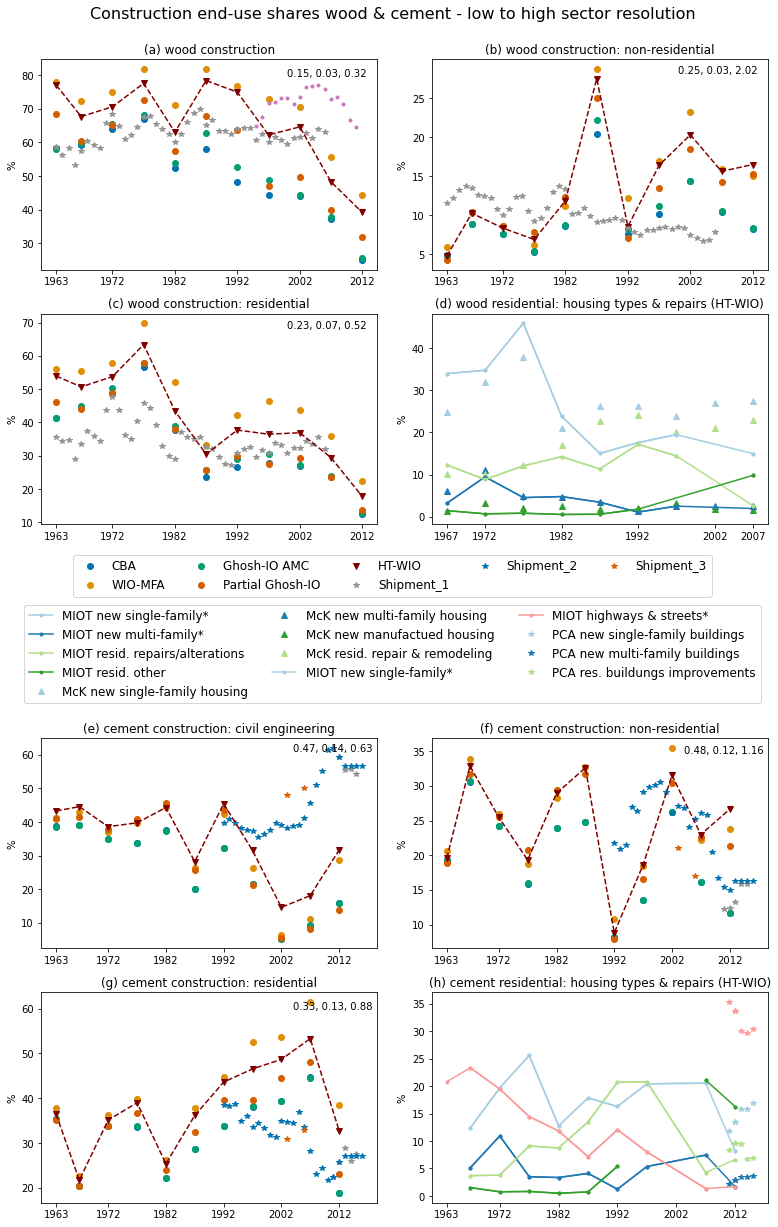


Figure 3: Comparison of end-use shares derived from U.S. monetary input output tables (MIOTs) for 11 data points between 1963-2012 generated with five input-output approaches (see section 2.1), with industry shipment data in physical units (see section 2.3) at medium (1) and low (2) sector aggregation. 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. The three shown end-use categories for cement do not do not represent 100% of total use – as categories such as ‘ready mix concrete’ cannot be distributed without assumptions (see section 3.1.4; coverage by three categories is, e.g. e.g. 2012: 80%, 2007: 86%, 2002: 86%, 1997: 89%, 1992: 97%, 1987: 96%)

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 category (in HT-WIO results: 91-99% among years). When further disaggregating ‘construction’ into the categories ‘civil engineering’, ‘non-residential’, and ‘residential’, we found rather large relative median deviations between 33-48% (and larger outliers with 63-116%), albeit coarsely similar temporal trajectory. These large deviations were probably due to misclassification 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 relative median deviation of MIOT and PCA data for 2012 were 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 sets of ‘material sectors’ in MIOT-based methods, i.e. the assumed MIOT sectors that receive material input from exogenous and initially distribute it to downstream industries, as well as WIO-MFA mass filter design 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 ‘material sectors’ and mass filters for the methods WIO-MFA and HT-WIO (see section 2.3). Results showed that for mass filters, deviations of ca. 30% occurred, while much larger deviations showed for selection of ‘material sectors’ (up to 91%), underlining the importance of matching these sectors closely to the material flows of interest. ‘Material sector’ choice is however restricted by MIOT sector representation, i.e. resolution and aggregated industries/products (for details see SI 1.3.2).

## EXIOBASE

Figure 4 panels 1a-I compare EXIOBASE-based results (HT-WIO) 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 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 the Data SI.

For panels 1 steel, we found rather good fit of shipments to MIOT-results for China[[3]](#footnote-3), 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 The UK (-73% to -82%). For aluminum we observed okay to good fit for China and India, with exception of Chinese transport (-54% to +20%), and rather bad fit for The UK. Strikingly, aluminum in machinery & appliances[[4]](#footnote-4) was strongly overestimated in MIOT-results for all three countries (with all except 3 data points with deviations >200%). This also applied to 10/11 additional country comparisons with shipment data from Liu and Müller (2013) shown in SI 1.3.3. For plastics, we could observe that the largest end-use according to shipment data (‘packaging’) has no representation in EXIOBASE as it is not distinguished as MIOT sector.

For panels 2, we observed 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 were 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 rather high shares for Japan, although shares for Netherlands and Norway are much higher in shipment than MIOT-based results (see SI 1.3.3). Unfortunately steel shipment data is very scarce and no comparison except for The UK could be conducted: when comparing with shipments in panel (1c), the low MIOT-based end-use shares for UK construction steel seem to be an artifact. Please note that the box / swarm plots are not weighted by the material consumption volume of respective countries.

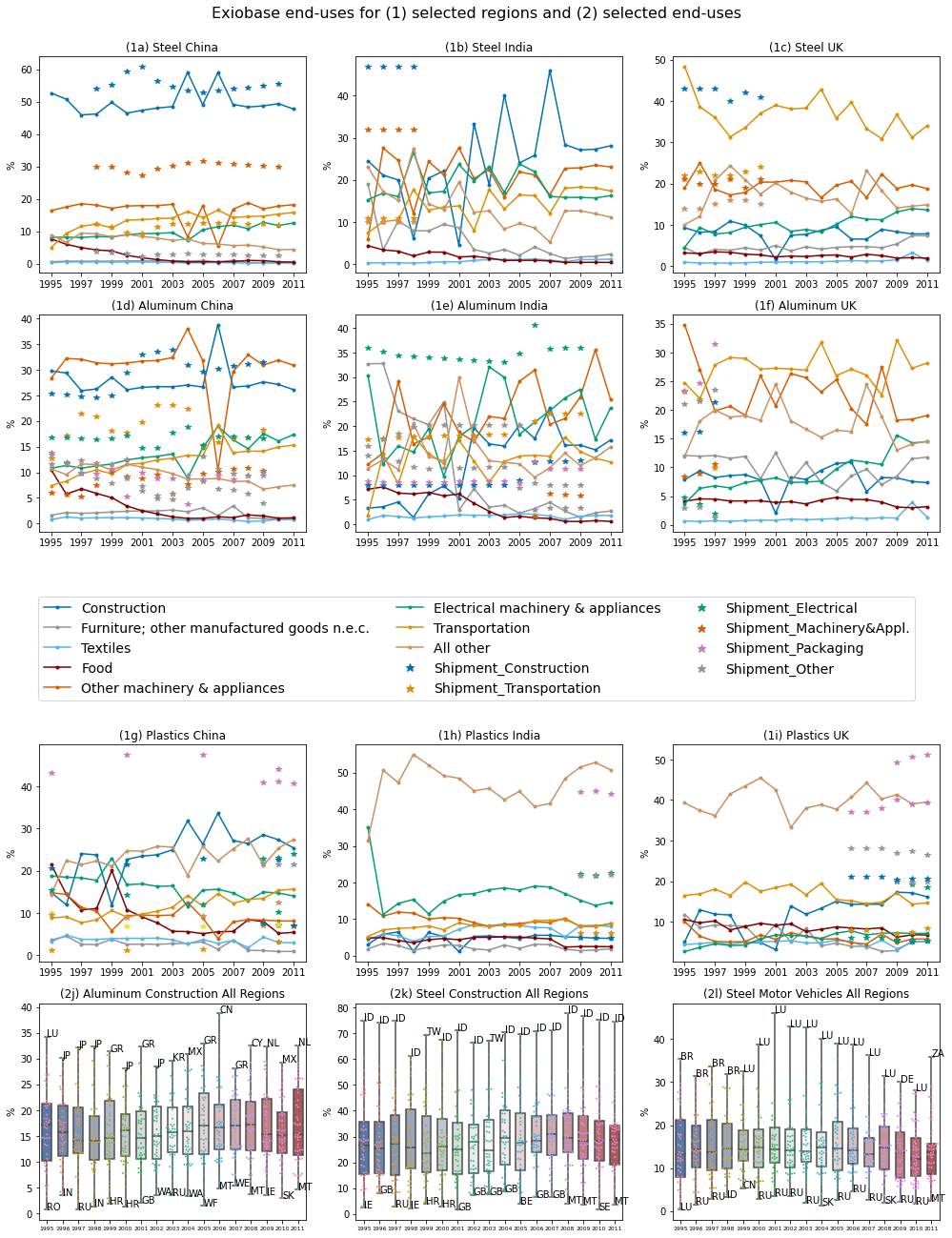


Figure 4: Comparison of end-use shares derived from EXIOBASE with the method of HT-WIO (see section 2), with industry shipment data in physical units (see section 2.3). The shown data sources for industry shipments are (Table 4): steel: China – Pauliuk et al. 2012, India – Pauliuk et al. 2013, UK - Pauliuk et al. 2013 / Dahlström et al. 2004; aluminum: all – Liu and Müller 2013; plastics: China – Jiang et al. 2020, UK - Plastics Europe 2006-2021(shares for whole EU), all - Euromap 2016. 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 approaches to industry shipments in physical units and see the fit for USA in detail and EXIOBASE countries / regions
* And from this to draw conclusions on the potential to derive end-use share information for many materials, countries and years from MIOTs, to complement scarce physical data situation on material end-use

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

* HT-WIO as theoretically best MIOT-based method, so we focused analysis of results on this approach
* In practice we saw varying fit of HT-WIO results to industry shipments, ranging from close agreement to large disagreements (see results section 3)
  + differences between materials for U.S. MIOT-results
    - aluminum good fit, wood rather good fit, steel bad fit (see 3.1.1)
    - for many material end-uses the temporal trajectory was similar for MIOT-based and industry shipment results (if also at different magnitude; much less so for EXIOBASE, little data for comparison with longer dynamics)
    - so MIOTs might give information about temporal changes, also if not about exact magnitude
    - raises the idea to complement available industry shipment data with MIOT-based temporal trajectories which can be calibrated on overlapping periods
* We ended up using the industry shipment data as benchmark for MIOT-based results
  + but we need to keep in mind that also industry shipments have a plethora of limitation (see diverging shipment sources in Figure 2 and limitations of shipments discussed in Streeck et al., in preparation)
    - for instance: large shares of materials delivered to end-use categories for which end-use is unknown such as service centers (e.g. USGS steel, see section 2.2); or ambiguous definitions of end-use categories, e.g. construction categories including construction machinery for USGS copper while not for USGS aluminum (see Streeck et al., in preparation)
    - looking at Figure 2 (f) for construction steel, shipment data sources diverge strongly and three sources with severe limitations which also makes it difficult to say anything about the validity of end-use shares derived from these industry shipments (see section 2.2)
  + Despite these limitations, industry shipment data for which we have reasonable information about end-use category definitions, coverage of material flows, etc. are still the best data source we can obtain in regards to ‘top-down’ statistics
    - Better / more flexible estimated might be conducted via bottom-up dMFA
    - next steps will include comparison of the bottom-up material stock estimates (per end-use category) with the stocks calculated with top-down dMFA and here derived end-use shares
* The initial hope was, that detailed MIOTs allow for high end-use product resolution from (see potential end-use resolution for U.S. MIOTs in Table 2). However, results on that point remain inconclusive
  + little physical data to compare with + partially already large deviations for aggregated end-use categories
  + we do know however that interpretation of MIOT results on the level of individual sectors are prone to error and these errors cancel out for aggregate indicators (Abd Rahman et al. 2021; Lutter et al. 2019)
  + however, Chen and Graedel (2015) and Chen (2017) show that for aluminum, for which we also here found particularly good fit for MIOT/shipment results (see Figure 2), rather detailed end-use categories derived from U.S. MIOTs partially show rather good fit to estimations with bottom-up methods (e.g. for Transportation sub-categories), although substantial deviations occur for some end-uses (e.g. for residential vs. non-residential structures; authors could not explain differences due to too little data available).
    - Also in the mentioned studies authors show that detailed estimates for some end-uses have data problems for bottom-up methods, while possible with MIOTs (e.g. for machinery sub-categories)
  + Besides the reliability issue, higher resolution of end-uses come with another problem:
    - sectors might not be assignable to preferred dMFA end-use categories due to unclear sector labels (e.g. ‘residential repairs’ cannot be assigned to either single- or multifamily housing with MIOT data but remains on the level of ‘residential’; see section 3.1.4)
  + described issues anyways only apply for detailed national MIOTs like for the USA or Japan
  + for MRIOs, which are interesting for covering many countries, sector resolution is low and allows for little detail

## Which parameters are crucial for approximating material end-use shares?

* We identified several parameters that strongly influence MIOT-based results for end-use shares and the comparison to industry shipments:
* importance of end-use product / sector definitions and system boundaries between data sources
  + end-use product / sector definitions are seldomly defined and remain unclear
  + therefore, to some degree we might end up comparing apples and pears in above comparisons (the system boundaries of MIOT end-use categories do not necessarily fully align with those of the industry shipments)
  + e.g. USGS copper shipments to end-use ‘buildings construction’ contains construction machinery (USGS 2015; CDA 2020), while MIOT-based results do not; or MIOT-based end-use shares for the sectors single-family & ‘multi-family ‘housing, buildings, structures’ seeming to include urban roads while unlikely the case for cement deliveries from the Portland Cement Association (see section 3.1.4)
  + the construction sector which is particularly important for material flows due to its use of large volumes of materials seems to be particularly ill-defined for detailed U.S. MIOTs
    - US MIOTs specify sectors according to NAICS (2017) industries. For construction however, NAICS codes are references with ‘23\*’ in the documentation (for MIOTs 2007/2012), which is the code for the construction sector as a whole, because BEA construction statistics do not align with NAICS industries
* importance of selecting the ‘material sector’ for MIOTs, i.e. the sector that functions as a kind of use-extension and directly distributes assumed material flows to downstream industry sectors in first supply chain step according to its monetary output structure (see sections 3.1.5; S 1.3.2)
  + choice is restricted by the sectors available in the MIOT at hand
  + when applying the end-use shares to a case study of material flows it is therefore important that the type of material flow is assigned to the MIOT sector(s) with closes fit to material flow system boundaries
* Issues regarding the matching of MIOT system boundaries to dMFA:
  + MIOT-based methods other than HT-WIO misclassify ‘intermediate products’ that are end-uses in dMFA sense which biases results of end-use shares for all categories
    - Packaging misclassified in particular, although it is an important end-use for the materials plastics, aluminum, glass
    - if packaging is re-defined as end-use through ‘Hypothetical Transfer’, not only this end-use is better represented, but also the end-use shares of categories other than ‘packaging’ decline accordingly through correct re-allocation of output to packaging (which is a more accurate representation for these categories as before packaging materials were incorporated into these and wrongly classified according to category label; e.g. plastic in packaging as plastic in cars)
    - precondition for working ‘Hypothetical Transfer’ is that the sector in question is differentiated in MIOTs
  + ‘Hypothetical Transfer’ also important for another reason: accounting for correct end-use meaning
    - 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)

When using WIO-MFA as the best identified method in Streeck et al. (in preparation) without Hypothetical Transfer, two issues connected to the question ‘What to do with the inputs to ‘service sectors?’ occur:

1) Simply deleting inputs to ‘service sectors’ will eliminate the ‘upstream demand pull effect’ of service final demand on materials (see 3.1.5/ S 1.3.2)

However, some WIO-MFA seem to pick the sectors for the material of interest, ignoring their embeddedness in the larger economy and respective interactions (CITE)

From the original publication, WIO-MFA wants to keep all ‘tangible goods […] with mass’ (Nakamura et al. 2007)

‘Nonphysical service components […] as trade, transportation, finance, and insurance are input without mass’ (Nakamura et al. 2007) and can thus be deleted

exceptions are e.g. repair sectors, which ‘can be regarded as input with mass to the extent that they alter the mass content of the object to which they are applied (Nakamura et al. 2007)

2) Additionally, also not deleting inputs to ‘service sectors’ comes with a problem: materials then end up in elusive end-uses according to the ‘service sectors’ labels (e.g. ‘government services’; for which then end-use needs to be assumed or the respective share of materials cannot be allocated to any end-use and ends up in categories such as ‘other’)

Here, Hypothetical Transfer seems like a good choice for staying close to the actual data while avoiding above mentioned problems

outputs of service sectors that can be assumed to be without mass (see above) can however still be deleted

Despite using Hypothetical Transfer, the non-matching system boundaries of MIOTs and dMFA might sometimes lead to interindustry connections, where interpretation of functional use in sectors cannot be avoided

* + - * For example for the U.S. MIOT for 2012, 9% of ‘Alumina refining and primary aluminum production’ is sold to ‘Soft drink and ice manufacturing’ via one crude material manufacturing supply chain step in the direct flow matrix (Z)
      * 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
      * These interindustry transactions might appear strange when taking a biophysical perspective but likely result from the monetary accounting principles (these might for instance also explain, why urban streets seem to be included in U.S. sector for ‘housing’ or ‘building’ (cf. 3.1.4), if the companies that build the houses also build the streets)

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

* For answering this question, the results for EXIOBASE are interesting in particular
* Fit of U.S. official national MIOTs to EXIOBASE varies
  + In tendency rather worse fit of EXIOBASE to industry shipments compared to U.S. national MIOTs (Figure 2)
* Comparing EXIOBASE fit to available country-level shipments for countries other than USA gives mixed picture
  + Rather good fit for China steel and aluminum end-use shares
  + Very large underestimation of steel use in construction for The United Kingdom (and large deviations for India also)
  + Strong overestimation of aluminum in machinery & appliances end-use for EXIOBASE for all 14 countries for which industry shipment data for comparison was available (see section 3.2)
* EXIOBASE has less sector resolution compared to U.S. national MIOTs which comes with certain drawbacks:
  + Sectors are often a mix of items with low processing degree (e.g. materials) and high processing degree (final products);
  + 🡪 thus, when choosing a ‘materials sector’ to derive end-use shares from its supply-chain distribution of these sector’s outputs, some output is delivered straight to final demand.
    - The share of the ‘material sector’s’ output that goes to final demand is accounted for as end-use with the label of the respective ‘materials sector’.
    - This output share cannot be assigned to a meaningful end-use category
    - Thus, the higher aggregated a MIOT, the lower the proportion of end-use shares that identifies meaningful material destinations (e.g., in comparison to more detailed MIOTs, a larger share of end-use then is, for example, ‘basic iron & steel and products thereof’ instead of ‘buildings’)
  + EXIOBASE does not distinguish a ‘packaging’ sector which strongly biases results for aluminum and plastics; this can partially be compensated by assuming material deliveries to ‘Food products’ as packaging
* Given the results comparison for EXIOBASE and industry shipments, the application of end-use shares to actual material flows should be done with caution
  + MIOT-base results should wherever possible be compared to physical data (being aware of limitations of physical data sources themselves)
  + If physical data not available for a certain country and year, comparison to data for other countries together with qualitative data (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?), and cross-checking with other country-specific statistics (e.g. construction industry activity etc.) might be a way towards still using MIOT-based end-use shares
  + Use of MIOT-based data will (like the use of industry shipments) need the detailed consideration of well-informed experts and might require additional research and comparison to secondary data sources
* Our results point towards the limitations of using monetary data for describing physical processes due to differing underlying system boundaries / objects of interest for reporting, as well as the challenge to assemble MRIOs from national MIOTs
  + For the first point, transaction-specific prices could provide for better approximations, but also for this data is scarce and without adequate physical data to compare with, we cannot be sure that resulting end-use shares are accurate
  + We also need to consider that EXIOBASE was not explicitly build for use with material flows
    - New database developments like GLORIA with focus on materials might deliver better results as potentially closer to material flow logic (Lenzen et al. 2021)
    - GLORIA also distinguishes the important construction sector into buildings and civil engineering (this will be one of our next steps)
    - We plan application of identified methods to GLORIA but the database is brand-new and still show some particularities that need to be solved, which leaves outside the scope of this work
  + Data needs to become better:
    - Transparent and mandatory reporting for material uses by e.g. industry associations
    - Further standardized reporting, i.e. different MIOT accounting practices in countries (pointed at by different fits for different countries in EXIOBASE, e.g. good for China, very bad for UK; what is wrong with construction flows in UK EXIOBASE?)

# Conclusions

* Conclusion on possibility to derive end-use shares for many materials, countries and years for application to economy-wide MFA

# Acknowledgements

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# Supplementary Information 1 (SI1)

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

Table S 1.1: Industry shipment data for countries and regions other than USA (although sometimes included). Some data sources are model outputs and no original 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 & light 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 were 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 evaluated the monetary deliveries to final demand for selected ‘material sectors’ which we then assumed to represent the shares of material-to-product allocations ( in Streeck et al. (in preparation), in contrast 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 evaluated their influence on results (see SI 1.3.1 for results). Table S 1.2 depicts the two sets of ‘material sectors’.

Table S 1.2: 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. All filter matrices can be found on the associated GitHub repository. 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 that are believed to have no physical counterpart, such as service flows (see main paper Table 1). 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., in preparation). 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. Then, depending on the scenario, the output and/or input of the raw material and service products was filtered, i.e. set to zero (see Table S 1.3 for detailed scenario description).

In addition to the mass filter, the WIO-MFA 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 which were used in Pauliuk et al. (2017). 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 **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’ was 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 product. 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 product, except if the product could unambiguously be identified as an end-use in the sense of dMFA 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 items for which the ratio implies intermediate but we classified as end-use product in yellow in the filter matrices (primarily the case for packaging, maintenance of buildings and structures, a few single sectors of furniture or electronics and all food sectors). 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 classified the product as end-use product by its label. Additionally, sectors that were assumed to only receive stock-building material inputs but are not considered to distribute further downstream were classified as end-use (e.g. agricultural sectors, as agricultural and food products are not focus of this work).

To calculate the Z/Y ratio, we only accounted for intermediate demand to sectors other than classified as ‘services’ according to our filter matrices, in order to avoid downstream shipments to ‘service’ sectors for which end-use can only be guessed (see section 2.3). 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. (in preparation), 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).

### S.1.2.4 Yield correction for industry shipments

We applied yield corrections to industry shipments in physical units for aluminum and wood (see ‘US\_IndustryShipmentData’ 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 available and yields 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 inconsistencies during allocation of individual to aggregated sectors may have occurred in the time series. In some tables, for instance, individual sectors were very detailed and could be assigned to different end-uses (*n* sectorst0 : *n* end-usest0), while in other years these individual sectors were more aggregated and could only be assigned to one end-use (*n* sectorst0 = *1* sectort1 : *1* end-uset0/1). Also, in early tables some sector labels were missing, in which case the product was allocated to the end-use that neighboring products referred to.

## S.1.2.5 Conversion factors wood volume to mass

To be filled in

## S.1.3 Additional results and result details

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

More details regarding the claims about the comparison of MIOT-based methods in section 3.1.2:

* As explained in section 3.1.2, the difference between HT-WIO and other methods would be more pronounced, if we did not interpret the use of 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 (Z), 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 main paper 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 main paper Figure 1, we transferred deliveries (=inputs) to service sectors to final demand during Hypothetical Transfer, which then increases 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 the remaining end-use categories.
* 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., in preparation). 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 main paper eq. 6) and deliveries to final demand are deleted (see Streeck et al. in preparation).

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

As mentioned in main paper section 2.3, we designed two scenarios for 1) different configurations of WIO-MFA mass filters, and 2) different sets of ‘material sectors’, i.e. the assumed MIOT sectors that receive material input from exogenous and initially distribute it to downstream industries. The base case, as well as scenarios are described in Table S 1.3. Results are depicted in Figure S 1.1 and values can be found in Data SI for ‘Figure 2 Sensitivity’.

Table S 1.3: Scenarios for evaluating the sensitivity of end-use shares derived via WIO-MFA and HT-WIO for the USA monetary input-output tables to manipulations in mass filters and ‘material sectors’ for potential extensions (for sector classifications such as ‘services’ please see mass filter matrices in GitHub repository)

|  |  |  |
| --- | --- | --- |
| **Scenario label** | **Sensitivity to** | **Description** |
| WIO-MFA | None / base case | 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 |
| 1) WIO-MFA\_filtDif | Keeping of service sector inputs | In difference to ‘base’: technological coefficients in **A** matrix kept for inputs (columns) to raw material and service sectors |
| 2) WIO-MFA\_extAgg/ HT-WIO\_extAgg | Variation of ‘material sectors’ (potential extension targets) | Extension modified by aggregation of two to three sectors as extension or switching of extension sector (see Table S 1.2) |

For the altered WIO-MFA mass filter scenario (\_filtDif), we found maximum relative deviations , of 28% for wood, 17% for steel, 23% for copper, 18% for aluminum and 29% for plastics. What is striking is that results of ‘WIO-MFA\_filtDif’ are lower than ‘WIO-MFA’ in all instances. This can be explained by the end-use shares assigned to the ‘service sectors’ for ‘WIO-MFA\_filtDif’ (transactions to these sectors are deleted for ‘WIO-MFA\_filtDif’ and thus zero), which result in lower shares for all other end-uses.

To determine end-use shares, we actually want to avoid the assignment of material use to ‘service sectors’, as the purpose in the sense of product stocks is unclear for these sectors (or subjective judgement needs to be applied when for instance determining the end-use of steel deliveries to ‘hotels and restaurants’; see main paper section 2.1.1). However, as argued in main paper section 2.3, we suggest that just deleting the inputs to service sectors also 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 methodological twist of Hypothetical Transfer (main paper section 2.1.1), which transfers the inputs to service sectors to final demand, which subsequently are identified as end-use product stocks (according to the label of the sector which’s output was transferred), while incorporate the service demand ‘upstream pull-effect’.

For the altered choice of ‘material sectors’, we here want to look at the difference of HT-WIO and HT-WIO\_extAgg. Looking at the materials for which for all years two sets of ‘material sectors’ were chosen (only for wood & plastics; see Table S 1.2), we find slight to strong deviation between the two sets, depending on end-use category. For wood, a maximum relative deviation of 25% can be observed for wood use in construction, 47% for transport, 33% for furniture, and 85% for packaging. For plastic use, the maximum relative deviation is 21% for construction, 91% for transport, 20% for packaging and 15% for furniture.

Thus, the choice of ‘material sector’ seems to influence results much stronger than the implemented differences in mass filter matrices. In particular, this choice strongly influences shares for individual sectors, which is much more uniform for mass filter deviations. This observation seems reasonable, given that the chosen ‘material sector’ acts like a use-extension to the industry system (determines the distribution of materials to downstream industry sectors in the first (direct) supply chain step). Selecting materials that have a rather different output structure, like for instance for plastics the aggregation of the sectors ‘Plastics material and resin manufacturing + Synthetic rubber manufacturing’ (HT-WIO\_extAgg) for plastic material flows instead of using just the former sector (HT-WIO) leads to higher end-use shares for ‘transport’ as the output shares for ‘Synthetic rubber manufacturing’ are much more geared towards this end-use sector than for ‘Plastics material and resin manufacturing’. Anyways, according to label, the selection of ‘Synthetic rubber manufacturing’ seems like a bad choice for distribution plastic material flows, but it illustrates that when applying the end-use shares to a case study of material flows it is important that the type of material flow (e.g. saw logs vs. veneer sheets) is assigned to the MIOT sector(s) with the closest fit as allowed by MIOT sector resolution (e.g. when sawmills vs. veneer producers are distinguished; if only one crude wood sector available there remains no choice but to assign to this one). However, the potential choice of ‘materials sectors’ is restricted by the sectors available in the MIOT at hand (if not making efforts to further disaggregate/aggregate).

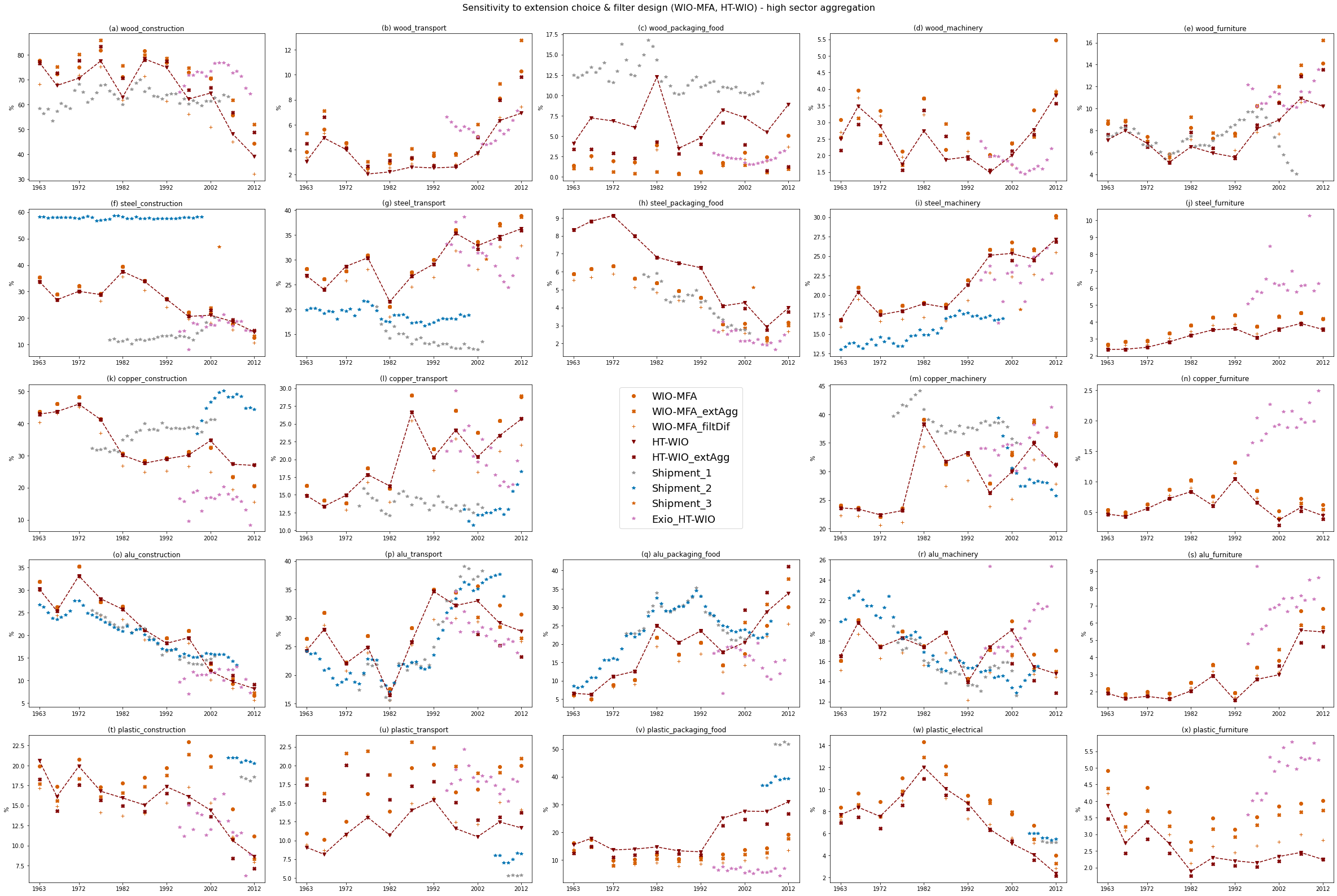
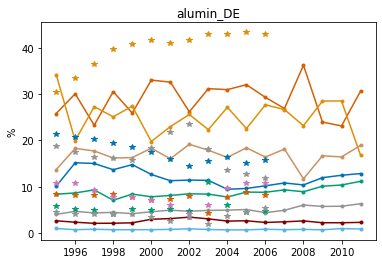
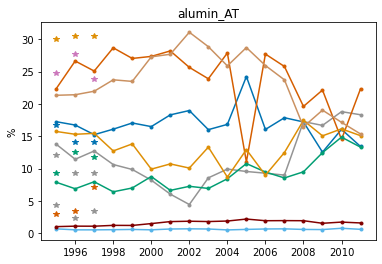
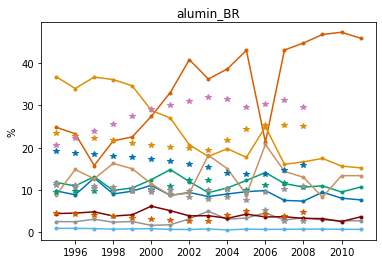
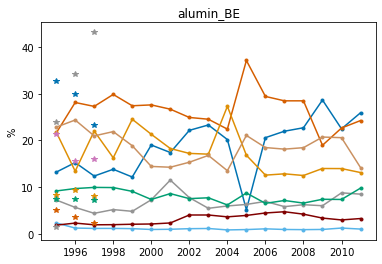
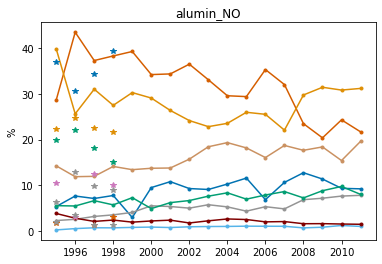
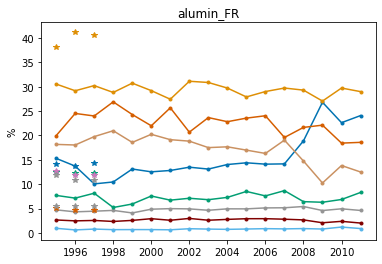
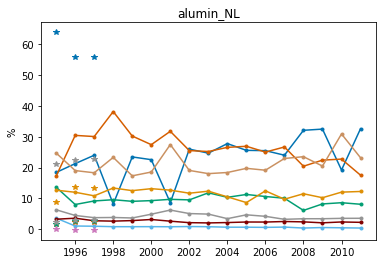
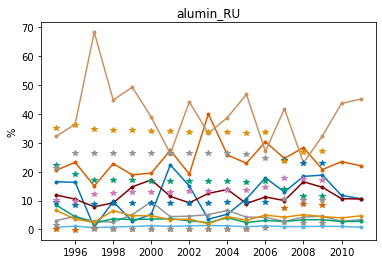
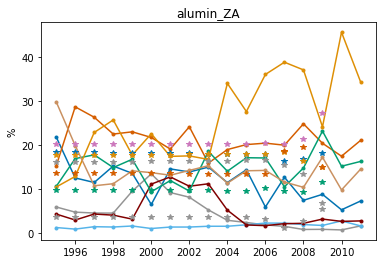
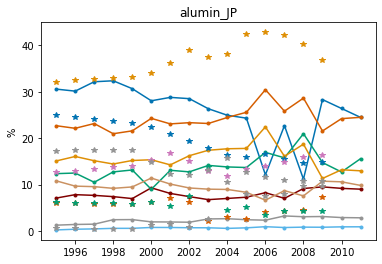


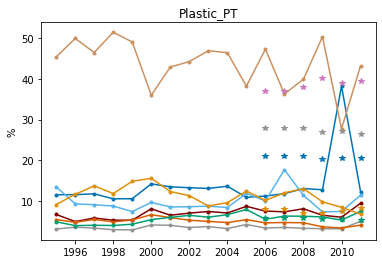
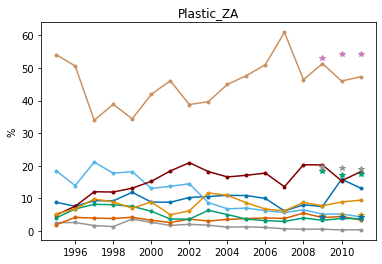
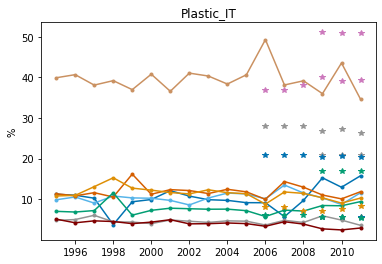
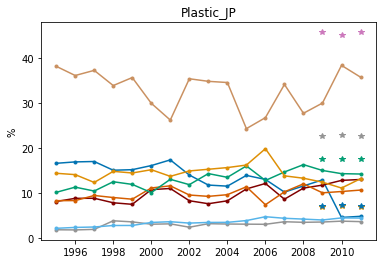
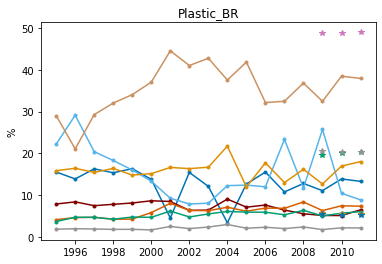
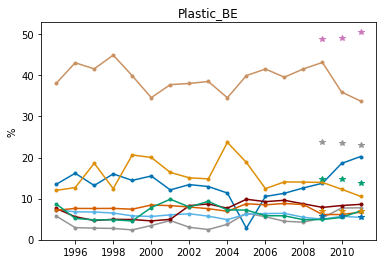
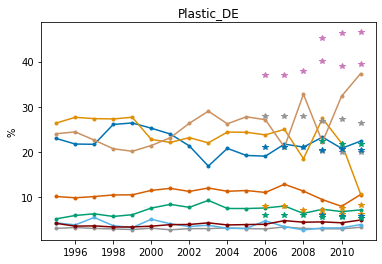
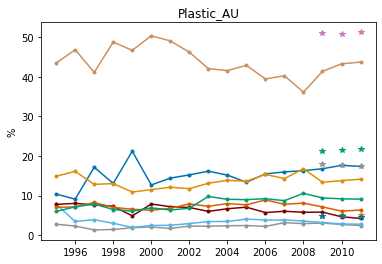
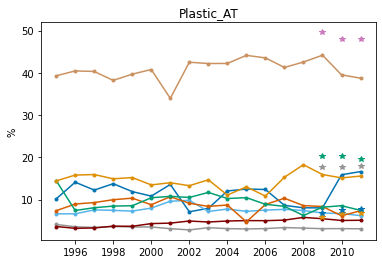
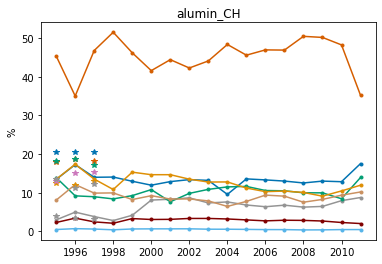
Figure S 1.1: Equivalent to main paper Figure 2 for scenarios that check sensitivity of WIO-MFA and HT-WIO to mass filters and choice of ‘material sectors’ (extensions)

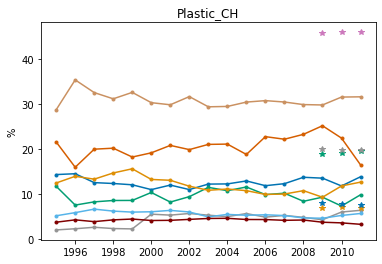
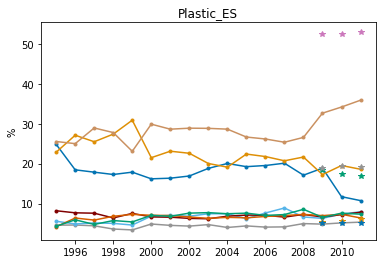
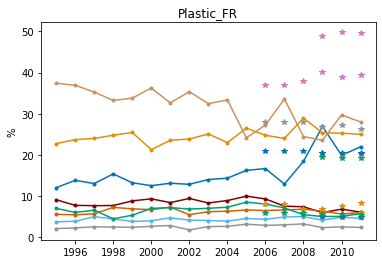
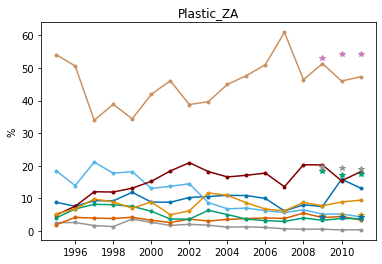
### S.1.3.3 Additional result plots EXIOBASE (MIOT-based results for HT-WIO)













Sources for industry shipments for above plots are: aluminum - Liu and Müller 2013, plastics - Euromap 2016; Plastics Europe 2006-2021

### S 1.3.4 Potential additional points for discussion or technical appendix

* + 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.
    - 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.
    - 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)

# Supplementary information 2 (SI2)



# Data SI 1



Note: currently very small negative end-use shares can occur for individual MIOT sectors for Ghosh-IO AMC due to use of the scipy function pseudo-inverse (which allows to estimate inverse of actually singular matrix)

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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)
2. and for a single year for steel, and more years for copper, however with uninformative end-use categories (see Table 2) [↑](#footnote-ref-2)
3. for comparison to ‘Shipment\_Machinery&Appl.’ sum up EXIOBASE results for ‘Electrical machinery & appliances’ and ‘Other machinery & appliances’ [↑](#footnote-ref-3)
4. summary of EXIOBASE sectors 'Machinery and equipment n.e.c. ' and 'Medical, precision and optical instruments, watches and clocks' [↑](#footnote-ref-4)