A macro level of assessment of material circularity
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Chapter 4

Global distribution of material inflows to in-use stocks in 2011 and its implications for a circularity transition

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Abstract

In Chapter 3, we saw that around 40% of global raw materials that are extracted every year are accumulated as in-use stocks in the form of buildings, infrastructure, transport equipment and other durable goods. Material inflows to in-use stocks are a key component in the circularity transition, since the reintegration of those materials back into the economy, at the end of the stock's life cycle, means that less extraction of raw materials is required. Thus, understanding the geographical, material, and sectoral distribution of material inflows to in-use stocks globally is crucial for circular economy policies. Here we quantify the geographical, material, and sectoral distributions of material inflows to in-use stocks of 43 countries and 5 rest of the world regions in 2011, using the global, multiregional hybrid-units input-output database EXIOBASE v3.3. Among all regions considered, China shows the largest amount of material added to in-use stocks in 2011 (around 46% of global material inflows to in-use stocks), with per capita value comparable to high income regions such as Europe and North America. In these latter regions, more than 90% by mass of in-use stock additions are comprised by non-metallic minerals (e.g. concrete, brick/stone, asphalt, and aggregates), and steel. We discuss the importance of understanding the distribution and composition of materials accumulated in society for a circularity transition. We also argue that future research should integrate the geographical and material resolution of our results into dynamic stock-flow models to determine when these materials will be available for recovery and recycling.

Keywords: Circular economy, in-use stocks, capital formation, multiregional hybrid-units input-output tables

4.1. Introduction

Global resource extraction has increased from 7 Gigatonnes (Gt) in 1900 to 89 Gt in 2015 (Fishman et al., 2016; Haas et al., 2020). Furthermore, a large amount of materials is extracted to produce durable goods that are accumulated by society (IRP, 2019). These materials accumulated as durable goods are called either in-use stocks or built/manufactured capital, and consist of buildings, infrastructure, machinery and other durable goods (OECD, 2008). Additions to in-use stocks account for almost half of the global resource extraction (Haas et al., 2015; Krausmann et al., 2017). From an environmental perspective, the production of capital stocks is responsible for around 20% of global CO_2eq emissions (UNEP, 2019) and for almost 40% of the material footprint of high-income countries (Tukker et al., 2014).

The materials stored in in-use stocks can in principle be reintroduced in the economy as secondary materials, when these stocks reach their end-of-life (Lanau et al., 2019; Mayer et al., 2018; Pauliuk & Müller, 2014). This reintroduction would be in line with paradigm of the circular economy (Ellen MacArthur Foundation, 2015; Kirchherr et al., 2017), according to which such a reintroduction would lead to decrease primary resource extraction, waste and emissions (Aguilar-Hernandez et al., 2018; Mayer et al., 2018). Several governments have encouraged the implementation of circular economy measures in order to promote resource efficiency as well as sustainable production and consumption (McDowall et al., 2017). However, most policy measures proposed, for example in the Circular Economy Action Plan brought by the European Commission (EC 2020), do not pay attention to inflows to and outflows from in-use stocks as a potential avenue to promote circularity. We believe that keeping track of such material flows is essential for understanding the potential for a circularity transition (Pauliuk et al., 2012; Stahel & Clift, 2015).

Material flows into and from in-use stocks have traditionally been assessed through material flow analysis (MFA), which is an approach which traces the flow of materials through socio-economic activities (Eurostat, 2013; Graedel, 2019). For example, multiple MFA studies have estimated the inflows and outflows of materials, such as metals (Dong et al., 2019; Gorman & Dzombak, 2020; Miatto et al., 2017; Pfaff et al., 2018; Zeng et al., 2018) and construction materials (Deetman et al., 2020; Marinova et al., 2020; Schiller et al., 2017; Wuyts et al., 2019) in different countries and world regions. More comprehensive MFA have been used to examine the global stock-flow dynamic (Krausmann et al., 2018; Nakamura et al., 2017; Pauliuk, Kondo, et al., 2017; Wiedenhofer et al., 2019), showing the evolution of the material composition of in-use stocks as well as the amount of waste recycled worldwide. A few studies have examined the relation between in- and outflows to and from in-use stocks by using hybrid-units and physical input-output analysis (Aguilar-Hernandez et al., 2019; Beylot & Villeneuve, 2015; Hoekstra & van den Bergh, 2006), an alternative top-down approach which offers a comprehensive view on the economy and economic sectors. For example, the most detailed global, multiregional input-output table in hybrid units (MR-HIOT) EXIOBASE covers 43 countries and 5 rest of the world regions, with a resolution of 163 sectors and 200 product categories per country/region. Although inflows to in-use stocks in both specific countries and in the global economy have been studied before, we believe a better geographical, material, and sectoral resolution is required to provide insights on where the largest opportunities for increased circularity might be.

Here we examine the geographical, material, and sectoral distributions of material inflows to in-use stocks in 2011, using the MR-HIOT EXIOBASE version 3.3.18 (Stefano Merciai & Schmidt, 2018; Schmidt & Merciai, 2017) and ancillary World Bank (2020) data. We estimate material inflows to in-use stocks of 43 countries and 5 rest of the world regions for 12 material categories (non-metallic minerals, steel, etc.). At the sectoral level, we estimate the distribution of non-metallic minerals and steel in construction (including building and infrastructure), transport, the rest of industries, and final demand categories. Furthermore, we distribute the global material inflows to in-use stocks per country and region in per capita terms (i.e. tonnes per capita), covering different income categories (e.g. high, middle and low income). In contrast to the existing literature, we provide a higher geographical, material, and sectoral resolution (see data_resolution spreadsheet in Data_validation, supporting information). This chapter hence provides essential information to support the current discussion on the opportunities for a global circularity transition.

In the next section, we describe how material inflows to in-use stocks are represented in the MR-HIOT EXIOBASE. We then present our results for the global distribution of various materials added to in-use stocks in different countries. Based on these results, we discuss the implications of additions to in-use stocks for a global circularity transition, and identify key aspects for future work on this topic.

4.2. Method

4.2.1. Material inflows to in-use stocks in the MR-HIOT EXIOBASE

We use the latest version of global, multiregional hybrid-units input-output table (MR-HIOT) from the EXIOBASE database v3.3.18, which includes 43 nations and 5 rest of the world regions (Stefano Merciai & Schmidt, 2018; Schmidt & Merciai, 2017). The MR-HIOT EXIOBASE flows are represented in mass, energy, and monetary units.

Material inflows to in-use stocks are represented in the extension of stock additions. This extension shows the gross material inflows to in-use stocks in mass units in intermediate and final demand categories. Stock additions extension is formally calculated as a residual in a mass balance of resource extraction, waste and dissipative emissions (Mayer et al., 2018; Schmidt & Merciai, 2017; Suh, 2004), as follows:

$$m + r + w_{rec} = e + b_{IC} + w_{sup} + s_{add} \, , \qquad [4.1]$$

where m represents the sum of imported materials, r is domestic resource extraction, w_{rec} is recovered or recycled materials, e is material export, b_{IC} corresponds to dissipative emissions, and other combustion and biomass residues from industries and final demand, w_{sup} is waste generation, and s_{add} represents material added to stocks (Aguilar-Hernandez et al., 2019). The latter variable is conceptually the material inflows to in-use stocks in a period, which is the focus of this chapter.

Figure 4.1 shows a simplified representation of the MR-HIOT based on Donati et al. (2020) and Towa et al. (2020). Capital letters indicate matrices of: intermediate demand (Z) which includes domestic intermediate demand and international trade in intermediates; final demand (FD) which includes domestic final demand and international trade of final goods and services; and extensions of resource extraction (R); waste supply and use (W); dissipative emissions

(B_{IC}); and stock additions (S_{add}). The stock additions extension represents the actual manufactured capital of an economy in physical terms, which are material inflows to in-use stocks in a specific year. Furthermore, S_{add} is a matrix in which rows represent material types (see material_class spreadsheet in Data_S3, supporting information), and columns cover all industries and final demand categories for each country/region (see industry_class and fd_class spreadsheets, Data_S3, supporting information). The MR-HIOT EXIOBASE extensions were developed by the integration of multiple databases of international institutions, for example, Food and Agriculture Organization of the United Nations (FAO), International Energy Agency (IEA), Eurostat, and Ecoinvent (Stefano Merciai & Schmidt, 2018). In particular, waste extension in the MR-HIOT EXIOBASE was generated by the collection of several data sources (see table 2.9 in S Merciai et al., 2014), and by the application of the gap-filling procedure (Stefano Merciai & Schmidt, 2018) when there was a lack of data for waste flows.

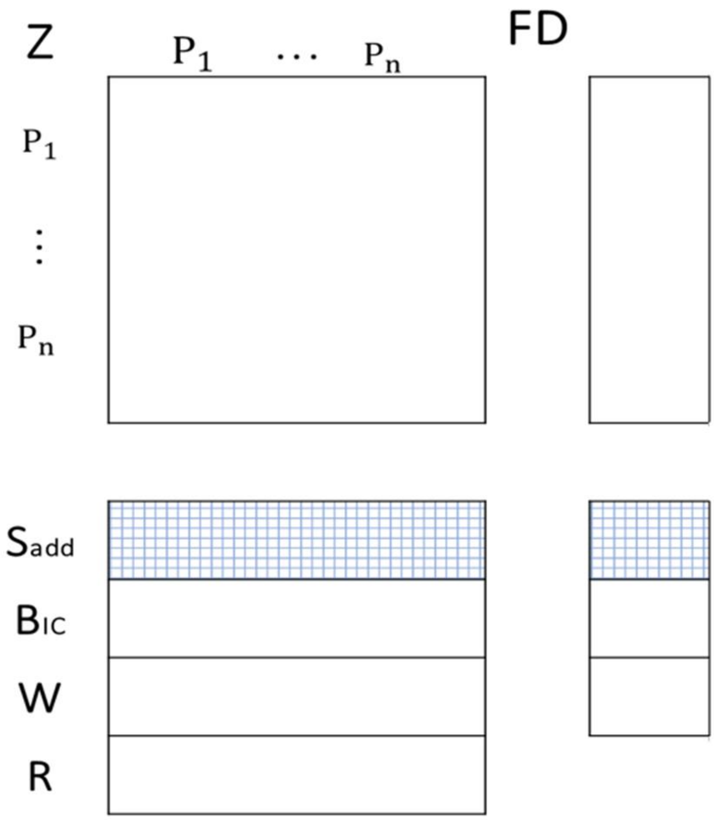

Figure 4.1. Simplified global, multiregional hybrid-units input-output table (MR-HIOT). FD = final demand matrix; Z = intermediate demand matrix; P = product or service; R = resource extraction matrix; W = waste supply and use matrix; B_{IC} = dissipative emission matrix; S_{add} = stock additions matrix. Elements in Z, and FD are in hybrid-units as monetary (i.e. M.EUR), energy (i.e. Terajoules), and mass units (i.e. tonnes). Elements in extensions R, W, B_{IC}, and S_{add} are in mass units. Blue large grid lines correspond the elements represent the material inflows to in-use stocks in mass.

As the stock additions in the MR-HIOT might be confused with the representation of capital formation in a traditional input-output table, it is important to highlight the main differences between the two accounting systems. In a traditional monetary input-output table, stock additions are represented by gross fixed capital formation (GFCF), which accounts for the economic value of fixed assets used for productive purposes in an economy (Södersten et al., 2018b, 2018a; Weisz & Duchin, 2006). According to the System of National Accounts 2008 (UN, 2009), fixed assets are defined by the asset boundary that differentiate which durable goods are accounted as GFCF or not. For example, consumer durables (e.g. washing machine and other home appliances) and small tools (saws, e.g. saws, knives, axes, and hammers) are not accounted in GFCF, despite having a lifetime longer than one year (UN, 2009). In contrast, stock additions extension in the MR-HIOT EXIOBASE includes all the material added to the in-use stocks in one year, which include fixed assets plus the rest of durable products. This follows the definition of gross stock additions used by the Economy-wide Material Flow Accounts (EC, 2001).

4.2.2. Estimating the global distribution of material inflows to in-use stocks

We quantify material inflows to in-use stocks of 43 countries and 5 rest of the world regions for 2011 using the stock additions extension from MR-HIOT EXIOBASE. This extension contains 12 material categories linked to durable good added to in_use stocks (as in material_class in Dataset_S3, supporting information). Algebraically, the total stock additions of material m in country c for year t (i.e. $S^{T}_{m,c,t}$) is equal to the sum of material stock additions in industries ($S^{I}_{m,c,t}$) plus the sum of materials accumulated in final demand ($S^{FD}_{m,c,t}$):

$$S^{T}_{m,c,t} = \sum S^{I}_{m,c,t} + \sum S^{FD}_{m,c,t}. \quad [4.3]$$

From equation 4.2, it is important to notice that the accounting of stock additions in the MR-HIOT allows for the allocation of durable goods in industries (as intermediate demand) and final demand categories. This means the material inflows to in-use stocks can be allocated to each industry as well as households, non-profit organizations serving households, government, and gross fixed capital formation.

To obtain the distribution of stock additions per material type at sectoral level, we distinguish 3 categories associated with intermediate demand (i.e. construction, transport and equipment, and rest of industries), and one aggregated final demand category. Stock additions to the construction sector per country and material type ($S^{C}_{m,c,t}$) is directly taken from stock additions extension where the material inflows to in-use stocks in the construction (including building and infrastructure) is allocated. For transport and equipment ($S^{V}_{m,c,t}$), we use an auxiliary extension of machinery, which contains the accumulation of transport equipment products (i.e. motor vehicles, trailers and semi-trailers, and other transport equipment) by all intermediate industries. Stock additions to final demand ($S^{FD}_{m,c,t}$ as in equation 4.2) comprises the material accumulated in final demand categories, i.e. households, non-profit organizations serving households, government expenditures, and gross fixed capital formation. We distinguish the sum of $S^{FD}_{m,c,t}$ from other industries because $S^{FD}_{m,c,t}$ includes part of the material accumulated for construction and transport purposes, for example, when households purchase residential housing or private vehicles. Material inflows to in use-stocks for the rest of industries ($S^{R}_{m,c,t}$) were calculated by the difference between the total stock additions and the sum of construction, transport and equipment, and final demand categories per country and material type, as follows:

$$S^{T}_{m,c,t} = S^{C}_{m,c,t} + \sum S^{V}_{m,c,t} + \sum S^{FD}_{m,c,t} + S^{R}_{m,c,t} \;\; ;$$

$$S^{R}_{m,c,t} = S^{T}_{m,c,t} - \left(S^{C}_{m,c,t} + \sum S^{V}_{m,c,t} + \sum S^{FD}_{m,c,t}\right). \quad [4.3]$$

4.2.3. Regression analysis

We develop a cross-country, regression analysis of material inflows to in-use stock and gross domestic product, purchasing power parity (GDP-PPP) per capita to evaluate the relation between gross stock additions and the different levels of economic development. In the past, material and environmental indicators have been correlated to GDP-PPP, indicating that affluence is one of the main drivers for environmental pressures (Aguilar-Hernandez et al., 2019; Tisserant et al., 2017; Wiedmann et al., 2015). Furthermore, Krausmann et al. (2017) showed that global material stocks (i.e. total in-use stocks) have increased in a similar rate as the GDP-PPP from 1900 to 2010, in which stock productivity (i.e. (GDP/material stock) has not changed significantly over the past century. In this chapter, it is not possible to establish a relation between GDP-PPP and global material stocks through time because this requires the development of long time series, which are currently missing in the MR-HIOT. However, material inflows to in-use stocks can be correlated to affluence to identify whether there are major differences of stock additions across different countries in one period. Algebraically, the relation between S_{add} and GDP-PPP per capita category is expressed as follows:

$$S_{add}\ /\mathrm{cap} = \mathrm{k}(\mathrm{GDP/cap})^{\alpha}, \qquad [4.4]$$

$$\log(S_{add}/cap) = \log(\mathrm{k}) + \alpha\log(\mathrm{GDP/cap})\ , \qquad [4.5]$$

where S_{add}/cap represents the material inflows to in-use stocks per capita; GDP/cap indicates GDP-PPP per capita; α is the elasticity coefficient; and $\log(\mathrm{k}) = \beta$ is a constant parameter in the linear model. The elasticity α represents the percentage change in S_{add}/cap when there is a 1% change in GDP-PPP/cap. To distinguish income groups, we used the classification used by the World Bank Atlas method (2019). We matched 45countries and 3 rest of world regions from MR-HIOT EXIOBASE with 223 countries from World Bank Atlas method (2019), and, then, weighted based on GDP-PPP per capita to obtain the income groups of selected countries or regions (see country_class spreadsheet in Data_S3, supporting information).

A detailed list of stock additions classification, the Python code used for the calculation, results, and data validation are available in supporting information (https://github.com/aguilarga/gds_supporting_information).

4.3. Results

4.3.1. Global distribution of material inflows to in-use stocks

In 2011, the total global stock additions amounted to around 30 Gigatonnes (Gt). For comparison, this amount represented 40% of global material extraction, while about 54% of materials were extracted for food and energy purposes (which were converted into dissipative emissions from fuel combustion) and the remaining 6% were accounted as waste flows in the respective period (Aguilar-Hernandez et al., 2019). 46% of global material inflows to in-use stocks (14 Gt) were accumulated in China. While high income countries (e.g. United States, Japan, and countries in the European Union) accumulated around one-quarter of global stock additions (7.3 Gt), the material inflows to in-use stocks in lower middle and lower income economies constituted 10% (2.9 Gt). The rest of material inflows to in-use stocks were accounted for upper middle and middle income regions (i.e. around 6.1 Gt or 20% of global stock additions), such as Latin America and the Asian-Pacific region.

In per capita terms, the global material inflows to in-use stocks averaged 4.3 tonnes per capita (t/cap) in 2011 (see Figure 4.2(b)). For high income countries, the average value was 7.0 t/cap, where the highest values were presented in Luxembourg (19.1 t/cap), Finland (15.2 t/cap), and Norway (14.7 t/cap). This is a common trend for other material use and environmental indicators, where nations with larger affluence and low population density showed the highest values per capita (Tisserant et al., 2017; Tukker et al., 2016; Wiedmann et al., 2015). In China, the value of material inflows to stocks was 10.4 t/cap, which is twice as large as the global average. However, the evolution of in-use stocks in China differs from high income economies where high levels of material accumulation have been taking place for over a century. Instead, in China high levels of material inflows to in-use stocks have only been observed in the past four decades (Krausmann et al., 2017; Wiedenhofer et al., 2019). With the exception of China, the stock additions per capita in upper middle and middle income economies ranged from 0.9 t/cap to 5.2 to/cap. The value in lower middle and lower income countries averaged 1.2 t/cap, which includes Indonesia (1.5 t/cap) and African region (1.1 t/cap).

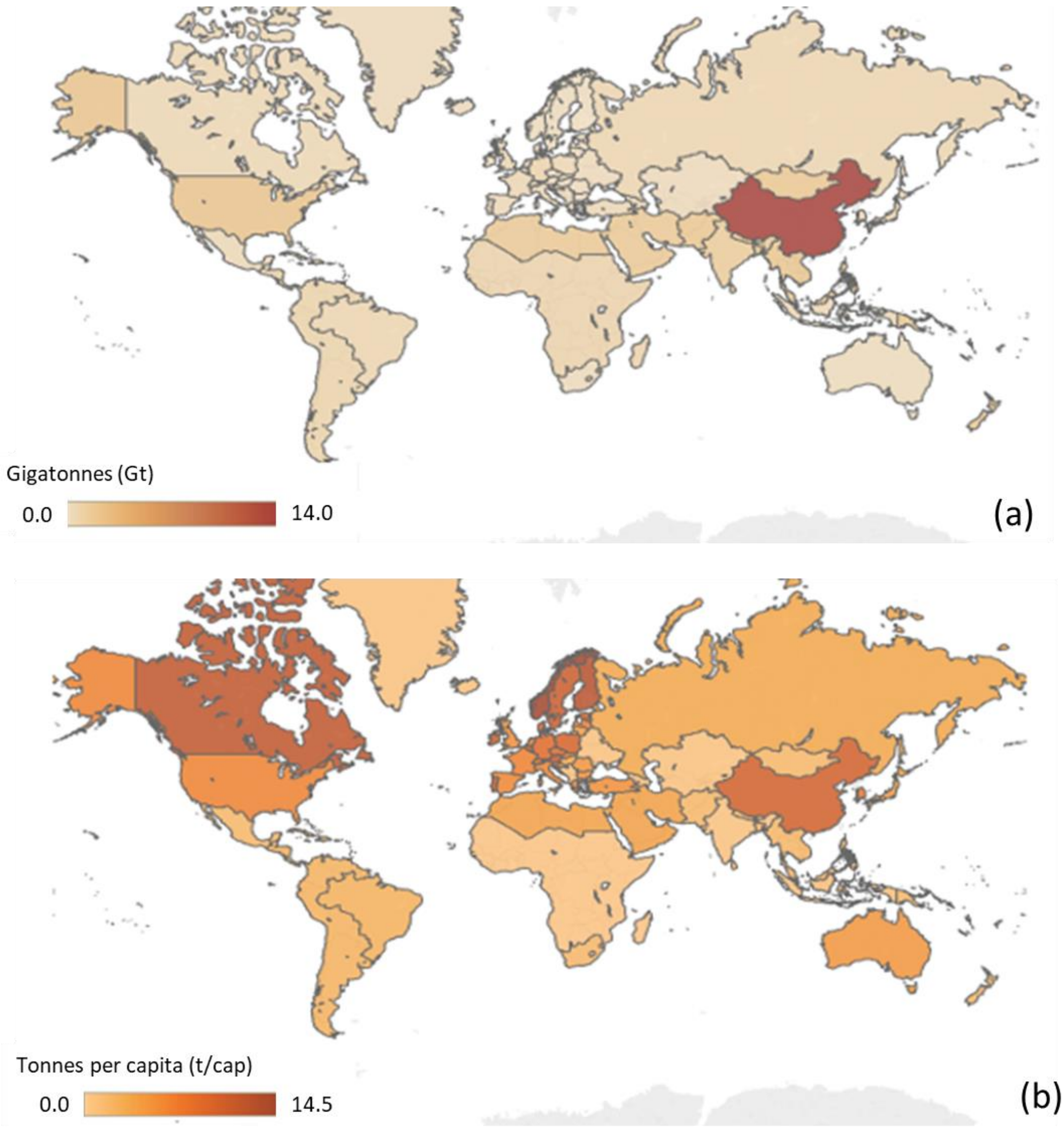

Figure 4.2. Global distribution of material inflows to in-use stocks in (a) absolute values, and (b) per capita for 2011. Total values are in Gigatonnes (Gt), and per capita values are in tonnes per capita (t/cap).

4.3.2. Material composition of stock additions

Global stock additions consisted of non-metallic minerals (87.9%), steel (5.2%), wood (4.5%), plastics (0.7%), paper (0.6%), glass (0.5%), other metals (0.4%), and textiles (0.2%). Non-metallic minerals include materials such as concrete, asphalt, bricks, aggregates and other durable materials used for buildings and infrastructure (Schmidt & Merciai, 2017). Figure 4.3 shows the material composition of inflows to in-use stocks for 5 countries and 6 selected regions covering different income groups in 2011. Material composition for all the 43 countries and 5 rest of the world regions is available in Dataset_S1, supporting information.

Non-metallic minerals ranged from 72% to 92% of the total stock additions, depending on country. In general, upper middle and middle income economies exhibited the largest share of non-metallic minerals in stock additions, such as Asian-Pacific (90% of 2.5 Gt) and Latin America (86% of 1.6 Gt). In high and upper middle income countries, non-metallic minerals represented a lower share of stock additions, for example, in Japan (81% of 0.6 Gt), Russia (77% of 0.5 Gt) and Australia (72% of 0.1 Gt).

Regarding steel added to in-use stocks, there is no noticeable difference between the composition of high and upper middle or lower income regions, except Australia (11% of 0.1 Gt) and Russia (15% of 0.5 Gt). For instance, the steel composition of stock additions in North America (5% of 2.5 Gt) and Europe (6% of 4.4 Gt) were comparable to those in Latin America (6% of 1.6 Gt) and the Asian-Pacific region (4% of 2.5 Gt).

Biomass durable products (as textile, wood and paper) varied from 2% to 20%, in which biomass composition in lower middle and lower income regions (e.g. India and African countries) were higher than other economies. The high share of biomass durable goods in lower middle and lower income regions is due to a large amount of wood stock additions (see sa_agg spreadsheet in Data_S1, supporting information), which can be associated with the use of wood materials for construction purposes.

Plastic materials ranged from 0.4% to 4% of total stock additions, where high income countries presented larger proportion of plastics added to in-use stocks (e.g. North America, Japan, and European countries). The fraction of glass in stock additions among different countries ranged from 0.1% in India to 3% in Australia. Other metals (including aluminum, copper, lead, and other precious metals) differed between 0.3% and 3% of total inflows to in-use stocks, without any trend across income class.

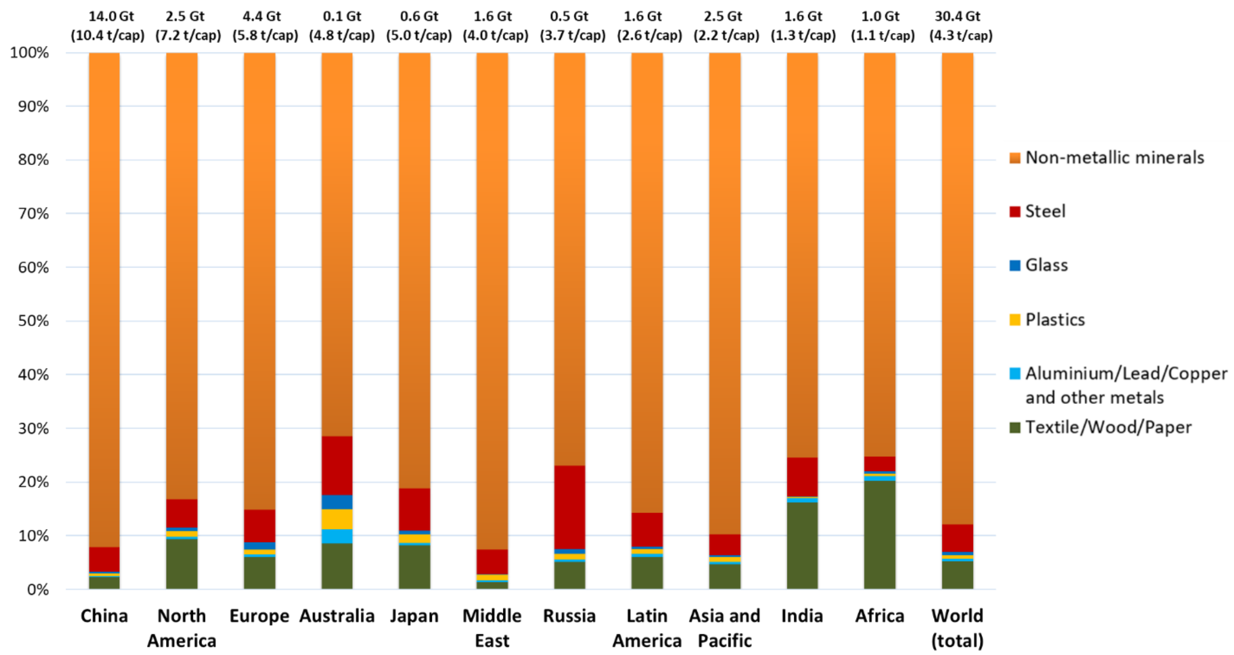

Figure 4.3. Material composition of inflows to in-use stocks for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per capita (t/cap). World (total) represents the sum of all selected regions and countries.

4.3.3. Sectoral distribution of inflows to in-use stocks

Figure 4.4 shows the distribution of the major material inflows to in-use stocks (i.e. non-metallic minerals, and steel) in 2011 across four sector categories: construction, transport and equipment, the rest of industries, and final demand categories. As explained in section 4.2.2., stock additions in construction comprise built environment and infrastructure, and the values were directly retrieved from the stock additions extension in the construction category. Transport and equipment consist of motor vehicles, trailers and semi-trailers, and other transport equipment, which are accounted in an auxiliary extension of the MR-HIOT EXIOBASE. Stock additions to final demand represent the material accumulated in final demand categories (e.g. households and government expenditures) as part of the material accumulated for construction and transport purposes, as well as other durable goods. For example, material accumulated when households purchase private cars or repair services for the vehicles. Rest of industries category was estimated by the difference between the total stock additions and the sum of construction, transport and equipment, and final demand categories (see equation 4.3, section 4.2.2.). Although more sectoral disaggregation is desirable, the selected economic activities are some of the most relevant for circular economy policies as construction and transport are considered two of the major contributors of resource use (Ellen MacArthur Foundation, 2015; Haas et al., 2015; Tukker et al., 2016).

More than 90% of non-metallic minerals were accumulated in the form of buildings and infrastructure (see non-metallic spreadsheet in Data_S1, supporting information). This confirms the importance of circular strategies in the construction sector discussed in previous studies (Jacobi et al., 2018; Jiang et al., 2019; Krausmann et al., 2018).

Steel accumulated by construction activities ranged between 16% and 46% of total steel added to in-use stocks (see steel spreadsheet in Data_S1, supporting information). Likewise, the fraction of total steel added to in-use stocks accumulated in the transport sector ranged from 1% to 14%.However, as final demand category also allocates material accumulated in construction and transport equipment, the share of steel in construction and transport is expected to be larger than the current sectoral distribution. The values of steel stock additions should include part of the direct purchases of households in construction and transport sectors, such as housing and private cars Considering stock additions in final demand, construction and transport accumulated between 64% and 86% of total steel stock additions.

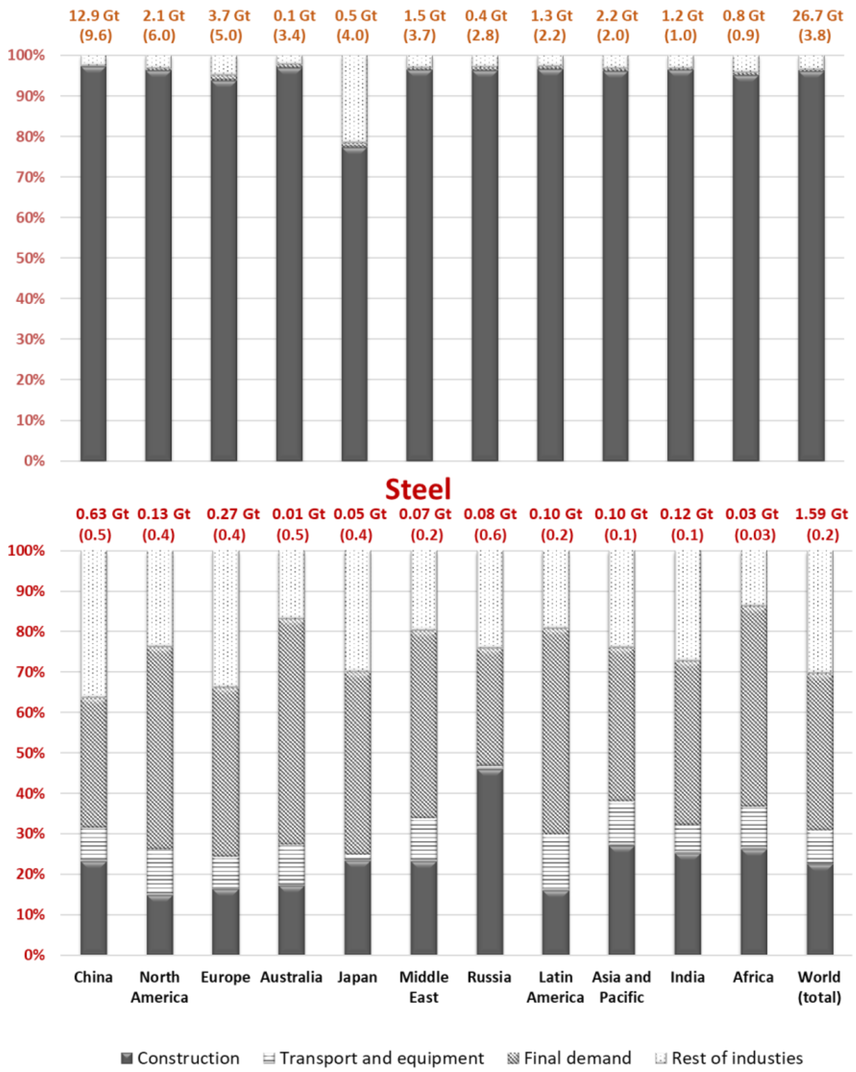

Figure 4.4. Sectoral distribution of inflows to in-use stocks for non-metallic minerals, and steel for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per capita (t/cap). World (total) represents the sum of all selected regions and countries.

These results are similar to those reported by Müller et al. (2011), in which their outcomes for 6 high income countries in 2005 showed that 60-70% of total steel was accumulated in construction and transport sectors (see Data_validation, and Table S2 in Appendix, supporting information). For a more comprehensive comparison, a further development of MR-HIOT is required to disaggregate the material stock addition of final demand categories in the respective classification used by MFA studies. A detailed comparison with previous MFA-based studies is available in Data_validation, supporting information.

The aggregated results are also similar to those reported by previous MFA studies, such as Haas et al. (2015) and Wiedenhofer et al. (2019) (see Data_validation and section 2 in Appendix, supporting information). This means that the results from the MR-HIOT approach are comparable to MFA studies, but still some improvements are required in the MR-HIOT system, which we will discuss as further research in section 4.4.2.

4.3.4. Relation between material inflows to in-use stocks and affluence

The cross-country, regression analysis of material inflows to in-use stocks and GDP-PPP per capita show that there is a positive correlation between stock additions and the degree of economic development (see Figure 4.5). A change of 1.0% in GDP-PPP per capita could lead to a change of 0.8% change in material inflows to in-use stocks (α=0.8). Furthermore, this elasticity coefficient suggests that high income and upper middle income economies were accumulated more materials because of the increase of affluence, which would imply more secondary materials from in-use stock removal in the future.

In comparison, some studies have demonstrated a positive correlation between GDP-PPP, material stocks and material use, showing differences between high income countries and developing world regions (see, for example, Krausmann et al., 2017; Wiedmann et al., 2015). Although the time limitation in the MR-HIOT (i.e. only one year), we still find a positive correlation between GDP-PPP and material inflows to in-use stocks. In this matter, it is important to notice that the viability of the relation between GDP-PPP and stock additions as an indication of drivers for changes in inflows to in-use stocks is still under debate.

Previous studies have suggested that material use and capital formation is driven by population growth and affluence (Krausmann et al., 2009; Steinberger et al., 2010). However, more recent literature suggest that it is not affluence by itself, but the rate of in which an economy changes its stock formation, which also considers whether a saturation of material inflows to in-use stocks might occur depending on the level of economic development (Bleischwitz et al., 2018; Haberl et al., 2020; Schaffartzik et al., 2019). For countries with a steady increased in fixed capital formation, the trend of stock formation is correlated to GDP. However, this relation is not maintained in the case of fast-developing economies, where capital investment grows faster than other regions (Bleischwitz et al., 2018). For example, the Chinese economy has shown a fast increase in stock formation, which leads to a high value of stock additions per GDP-PPP compared with other countries (Krausmann et al., 2017; Song et al., 2020; Soulier et al., 2018). This might explain the observation obtained for China (in figure 4.5), where the correlation between GDP-PPP and inflows to in-use stocks seems to differ in relation to other world regions. Further data improvements in the MR-HIOT are required to analyze properly the effect of the rate of stock formation, which we will discuss in section 4.4.2.

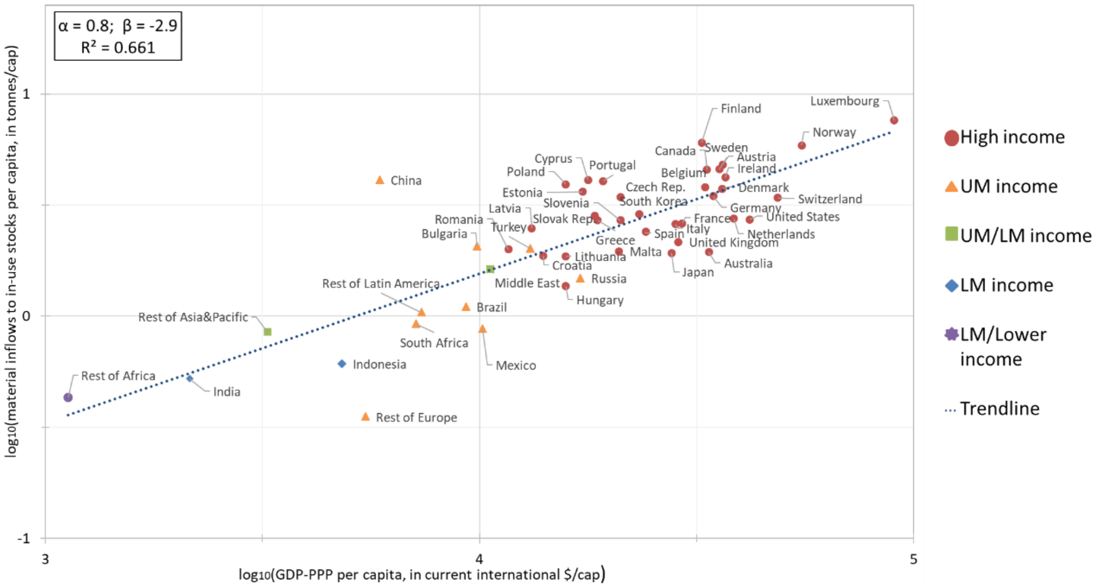

Figure 4.5. Logarithm of material inflows to in-use stocks (in tonnes/cap) over logarithm of gross domestic product, purchasing power parity per capita (GDP-PPP/cap), in current international $/cap). Red circles denote high income countries. Orange triangles indicate upper middle income (UM) countries. Green squares denote upper middle and lower middle income (UM/LM) countries. Blue diamond indicates lower middle income (LM) countries. Purple 6-point star indicates lower middle and lower income (LM/Lower) countries. Dark blue dot line represents the regression trendline, α is the elasticity, β is a constant parameter, and R^2 is the standard coefficient of determination.

4.4. Discussion conclusions

The purpose of this chapter was to identify the global distribution and composition of material inflows to in-use stocks in a specific period. Previous studies have shown the evolution of material flows to in-use stocks worldwide over a long time frame, which allowed them to make estimates of global stocks in use (Haas et al., 2020; Krausmann et al., 2017; see, for example, Wiedenhofer et al., 2019). These studies however had limited geographical resolution. For example, Krausmann et al. (2017) distinguished 3 world regions (i.e. industrialized countries, China, and other countries), and did not discern product groups and sectors contributing to capital stock formation. Such information is useful in identifying the priority products and sectors in which countries that could be most relevant for a circularity transition. We filled this research gap by quantifying material inflows to in-use stocks that consider a higher geographical, material, and sectoral resolution, acknowledging the database limitations used in this study in which detailed global physical material flows were available only for one year (i.e. 2011).

In 2011, almost half of the materials added to stocks were accumulated in the Chinese economy, whose per capita stock accumulation value was similar to those reported for high income countries. On average, high income regions (e.g. Europe and North America) accumulated 3 times more materials than lower upper and lower middle income economies (e.g. Asian-Pacific and African countries). This is comparable to resource consumption patterns at different levels of economic development, which support that capital formation is a key aspect of material use in a country or region (Jiang et al., 2019). The use of non-metallic minerals and steel constituted almost 95% of material added to stocks across regions.

Considering the relation between material inflows to in-use stocks and GDP-PPP per capita, high income and upper middle income countries will have more availability for future secondary materials as their current degree of affluence seems to drive more stock additions, which will become waste in the future (i.e. stock depletion or removal). Thus, the findings suggest that a circularity transition might occur in high income and upper middle income regions. Meanwhile lower middle and lower income region still in a phase of capital investment growth and material accumulation. Thus, we could assume that it would require a longer period before having a sink of secondary materials that enables a circularity transition in lower middle and lower income region. However, the correlation analysis did not consider potential circular improvements that can be implemented at early stages of product design, for example, where future material inflows to in-use stocks can be designed in more resource-efficient ways and with longer product's lifetimes. Such improvements will be discussed in section 4.4.1. Furthermore, the correlation analysis should be interpreted with caution as it does not include the total material stock and stock productivity, which could highlight the importance of the rate of stock formation instead of only considering the effect of changes in GDP on material inflows to in-use stocks. To determine whether the differences between countries are driven by the rate of stock formation, it is required the development of time series, and the integration of vintage models that allow to quantify total material and stock productivity through time in the MR-HIOT (see section 4.4.2. for further details).

4.4.1. Implications for a global circularity transition

Understanding how much and where materials are accumulated provides valuable information for resource management and which type of intervention can be applied to each country and region. For circular economy policies, four main circularity interventions have been proposed: closing supply chains (i.e. intervention for materials that are reintegrated into the economy through reuse, refurbishment or recycling), residual waste management (i.e. end-of-life materials discarded outside the economy), product lifetime extension (i.e. prolonging the lifetime of goods through product design, maintenance and repair), and resource efficiency (i.e. resource use optimization by producing more output with less input) (Aguilar-Hernandez et al., 2018).

Regarding materials inflows to in-use stocks, the design for longevity and resource efficiency is the circularity strategy that can be implemented in the shortest term. This is because the new materials inflows to in-use stocks can be designed for longevity with a right to repair and maintenance, as well as produced in a more resource efficient way. In the case of China, for example, both interventions can be applied to the construction sector, which comprised 97% of the total demand of non-metallic minerals and 23% of the total demand of steel. Extending the lifetime of in-use stocks could contribute to decreasing the need for new stock additions, thus reducing resources extraction and waste generation in the future. Furthermore, resource efficiency interventions can reduce the use of primary inputs to provide the same amount of output, which might imply less extracted resources per unit of in-use stock. However, the effects of lifetime extension should be assessed from a broader perspective than materials alone. Keeping older buildings and vehicles in stock could have a negative effect on the overall operational energy efficiency, so trade-offs should be considered in a dynamic and holistic manner, such as indicated in a recent report brought by International Resource Panel (IRP, 2020) , and Pauliuk (2020).

While residual waste management and closing supply chains are focused on minimizing waste generation, these interventions are more long term measures in the context of stock additions, where policies can benefit from information about the amount of materials that will be disposed as waste from a specific period. For instance, materials added to stocks in Europe during 2011 will potentially provide 4.4 Gt of materials to be reused or recycled, of which 85.1% are non-metallic minerals, 6.1% steel, 6.0% biomass durable goods, 1.3% glass, 1% plastics and 0.5% metals (as aluminum, lead, copper and other precious metals). However, it is important to notice that closing supply chain and residual waste management also have a role in the short term when a large amount of waste from in-use stock removal can be available at the present, in which material recovery and recycling would help to reduce the share of extracted materials.

4.4.2. Further research

Material inflows to in-use stocks were allocated in a consistent input-output framework, i.e. the global, multiregional input-output table in hybrid units (MR-HIOT) from EXIOBASE. However, there are several aspects that can contribute to improve the assessment of global distribution of material inflows to in-use stocks. Here, we present 3 main aspects for improving the current analysis (i.e. the need for MR-HIOT time series, allocating stock additions to capital stock in use by specific economic sectors, more detailed insights in stock additions composition, and uncertainty analysis), and concluding reflections.

4.4.2.1. The need for MR-HIOT time series

The MR-HIOT is currently available for just one year. Future research will need to develop time series, so that a more dynamic view on the integration of the global distribution of material inflows to in-use stocks can be obtained (Pauliuk et al., 2015; Wiebe et al., 2018). This will allow determining the size of the material reservoir from in-use stocks, which until now only has been quantified for individual materials, or for a limited number of countries and regions without a detailed sector classification (Krausmann et al., 2017; Pauliuk, Kondo, et al., 2017). For example, current data advancements from the Material Inputs, Stocks and Outputs (MISO) model (Wiedenhofer et al., 2019), and future data development (for example, from PANORAMA project (2020)) could serve as a basis for creating time series of a MR-HIOT in order to model the stock-flows dynamic with a high geographical, material and sectoral resolution.

4.4.2.2. The need for allocating stock additions to capital stock in use by specific economic sectors

The current MR-HIOT resolution has limitations by itself. For example, the analysis at sectoral level (see section 4.3.3.) presents an allocation by intermediate and final demand categories, which might be seen as main drawback because it might obscures a clear allocation of material inflows to in-use stock to functional types of in-use stocks including the sectors that use these stocks (i.e. an allocation by product/service categories). Capital stocks are in use by specific economic sectors (including household and government), and form the basis for production capacity and well-being (IRP, 2019; Tukker et al., 2016) . However, the MR-HIOT shows stock formation (or Gross Fixed Capital Formation) as a separate entity in a specific year, without allocating capital stock in use by economic sectors. Södersten et al. (2018a, 2020) demonstrated how investment matrices can be used to integrate such information in IOTs. In combination with information of different age cohorts as described by Pauliuk et al. (2017) and Sigüenza et al. (2020), this will allow creating dynamic stock vintage models that allows identifying where and when stock removals will take place. For example, the mean lifetime of a building can vary from 34 to 100 years depending on the country and region (Deetman et al., 2020). This implies that it takes a long time before material added to construction in-use stocks become available as scrap, and dynamic stock vintage models are required to determine when the material added to in-use stock in building construction will become available for recovery or recycling.

4.4.2.3. The need for more detailed insights in stock additions composition

The stock additions extension in the MR-HIOT can be improved by providing more detailed on stock composition. The current construction of the MR-HIOT allocates additions to in-use stocks for intermediate and final demand categories as part of mass balance procedure (Stefano Merciai & Schmidt, 2018). However, this approach does not allow to make a connection between the stock additions of different industries and respective products used by final demand. Ideally, the GFCF should allocate all the material added to in-use stocks in one year. However, in the MR-HIOT, there is an issue of using hybrid units (e.g. monetary and mass units) that restricts the estimation of stock additions in physical terms directly from GFCF as there are some services (such as construction) that account stock additions in monetary units. A way to address this issue is by developing a concordance matrix that combines product and industries categories to allocate stock additions in mass units, i.e. a matrix with industries in rows and products in columns, whose entries are all zeros except in entries where an industry aggregates a durable product. Such concordance matrix can be used to assign material inflows to in-use stocks per product/service, which can be converted into material categories (e.g. non-metallic minerals, and steel) through the use of the transfer coefficients that enable the distribution of material types per product/service (Stefano Merciai & Schmidt, 2018).

4.4.2.4. Data uncertainty

Another improvement for future analysis is the incorporation of a proper uncertainty analysis, which is important to evaluate the data reliability. We did include a data validation through a comparison of net stock additions (i.e. material inflows minus material outflows from in-use stocks) with previous MFA-based studies, which shows similarities when values are aggregated, but also some discrepancies at country level (see Data_validation, supporting information). A proper uncertainty analysis is still required to understand the reliability of MR-HIOT datasets. There are methods to estimate the uncertainties of multipliers in multi-regional input-output tables, and compare different databases (see, for example, Lenzen et al., 2010; Owen et al., 2014), which can be used as a basis for further uncertainty analysis in the MR-HIOT. This would require an effort of data collection for the model's input as well as the development of statistical method to propagate standard error through the different modules used in the MR-HIOT EXIOBASE.

4.4.3. Concluding reflections

We recommend that follow-up research should consider developing time series of a multiregional hybrid-units input-output framework so that a data set is created that works in the same way as dynamic material stock-flow models. The main difference is that the MR-HIOT time series will not focus on a specific material, but covers all material flows, and further discerns the products and sectors that create such in-use stocks. Currently, MRIOTs and the

MR- HIOT used in this chapter present capital investment as separate demand category, however, capital investment and in-use stocks ideally should be allocated to the production sectors that use such fixed capital. This requires the allocation of capital formation to using sectors via e.g. investment matrices, as elaborated by Södersten et al. (2018a, 2020). In combination with information of expected in-use stocks lifetimes, this will allow understanding which material stocks of which composition and in which sectors and countries will become available for material circularity, providing a way to identify which circular economy policies will be most effective with respect to time. Finally, further advancement of MR-HIOT should be developed along with the integration of uncertainty analysis that ensures the data reliability, and future comparison across the body of literature about a circularity transition.

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