A macro level of assessment of material circularity
Aguilar Hernandez, G.A.

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Author: Aguilar Hernandez, G.A.
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Chapter 6

General discussion

6.1. Introduction

This thesis explored the potential implications of material circularity on a macro scale. The starting point of this thesis was the application of EEIOA on assessing material circularity. From here, Chapter 2 investigated the EEIOA-based studies in the past 3 decades by a systematic literature review that summaries the EEIOA modelling framework of each circularity intervention. Next, Chapter 3 presented an empirical analysis of the current global material inflows and outflows, where the circularity gap metric was introduced and estimated for 43 countries and 5 rest of the world regions. Based on the results in Chapter 3, Chapter 4 showed the geographical, material type and sectoral distributions of material inflows to in-use stocks and its implications for implementing circularity interventions in the short- and long-term. Finally, Chapter 5 presented a meta-analysis of circular economy scenarios from 2020 to 2050, where future changes on GDP, employment and CO_2 emissions were examined. Overall, the integration of Chapter 2-5 aimed to provide a better understanding of the macroeconomic, social, and environmental implications of a circularity transition.

This thesis contributes to the macro level assessment of material circularity by: 1) bringing a better understanding of the opportunities and limitations of applying EEIOA on the assessment of material circularity; 2) showing how circularity interventions can be applied in multiple countries or regions depending their material inflows and outflows as well as the different stages of economic development; 3) providing a consensus of the macroeconomic, social, and environmental impacts of a circularity transition based on the information available up to date.

This chapter proceeds as follows: Section 6.2 presents the answers to each research question (RQ) proposed in Chapter 1; Section 6.3 discusses the limitations and further research; and Section 6.3. concludes with final remarks from the research and policy perspectives.

6.2. Answers to research questions

6.2.1. RQ1. *What is the state of the art of environmentally extended input-output analysis (EEIOA) on the assessment of circularity interventions?*

To address this question, 95 EEIOA-based studies that assess circularity interventions were systematically reviewed and evaluated in terms of the opportunities and limitations of EEIOA method on analyzing the impacts of material circularity (see Chapter 2). Based on the reviewed literature, a consensus on how to model circularity interventions using EEIOA was established. In general, modelling circularity interventions would require the use of physical and hybrid-units input-output tables that enable the integration of secondary materials and waste flows in the EEIOA framework (Lenzen & Reynolds, 2014; Nakamura et al., 2007; Reynolds et al., 2014).

Furthermore, the modelling of each circularity intervention requires different ways to adjust intermediate and final demand coefficients as well as the integration of data in input-output tables. Chapter 2 offers a synthesis of modelling approaches based on 4 circularity interventions: residual waste management, closing supply chains, product lifetime extension, and resource efficiency (see figure 2.4). First, residual waste management can be modelled through changes in the amount of waste received by specific waste treatment sectors (e.g. reducing waste from landfill to recycling activities). Second, closing supply chain can be modelled by adapting coefficients in input-output tables where reuse and recycling sectors are shown explicitly. Third, product lifetime extension can be modelled through changes in final demand and adjusting technical coefficients of specific economic sectors that represents an adjustment of the production recipe because of improving product design. Finally, modelling resource efficiency can be applied through adjusting the inputs while keeping the same output of certain product.

6.2.2. RQ2. *How much unrecovered waste is available to be reintroduced into the global economy as secondary materials in a specific period?*

This question was answered by defining and estimating the circularity gap of 43 countries and 5 rest of the world regions. Traditionally, the circularity gap did not distinguish between the amount of materials that are dissipated as emissions, accumulated as stock additions, or the waste generated from previous stocks (i.e. stock depletion) (Cullen, 2017; de Wit et al., 2018; Fellner et al., 2017). In Chapter 3, the circularity gap was redefined as waste generation plus stock depletion minus waste recovery (see equation 3.1), which represents the amount of unrecovered waste available for recovery or recycling in a specific period.

In 2011, the global material inflows amounted to 77 Gt, which comprises material extraction (74 Gt) and waste recovery (3 Gt). From the global material inflows, 40 Gt were used for energy and food purposes, 30 Gt was added to in-use stocks, and 7 Gt became waste. The total waste (i.e. waste generation plus stock depletion) was 9 Gt in this period. This means that the circularity gap was 6 Gt (i.e. total waste minus waste recovery), which represented around 8% share of the global material extraction. Thus, there was only a small fraction of unrecovered waste that can be used for material circularity.

For each country and region, the circularity gap differed in accordance with the level of economic development. For instance, high income regions (e.g. the European Union and North America) presented a circularity gap between 1.6 and 2.2 tonnes per capita (t/cap), doubling the global average (i.e. 0.8 t/cap). These regions presented a large level of waste recovery, but also higher stock depletion that was not recovered or recycled. On the other hand, the circularity gap of lower middle and lower income economies (e.g. the Asian-Pacific and African regions) showed an average of 0.4 t/cap. Despite their low degree of total waste compared with high income regions, lower middle and lower income countries presented a low level of waste recovery.

Using the circularity interventions described in Chapter 2, it is possible to identify which measures can contribute to reduce the circularity gap of nations (see figure 3.6). For instance, waste recovery can be increased through residual waste management because increasing waste recovery can be done by reducing landfill and incineration processes with recycling activities. Closing supply chains and resource efficiency are suitable interventions for reducing waste generation, as these interventions can re-introduce materials at different levels of the supply chain and use of less inputs per unit of total output that minimize the amount of waste produced. Product lifetime extension can reduce the future waste coming from old stocks by prolonging the lifetime of goods and delaying stock depletion.

6.2.3. RQ3. *Where are the materials accumulated in the global economy that could enable a circularity transition?*

To answer this question, the global distribution of material added to in-use stocks was estimated in Chapter 4. This study offered the geographical, material type, and sectoral distribution of material inflows to in-use stocks across 43 countries and 5 rest of world. As shown in Chapter 3, around 40% of global material extraction ends up as stock additions, which can be seen as the potential secondary material for a circularity transition, Thus, identifying the global distribution of material inflows to capital formation brings insights on where a circularity transition might occur worldwide.

Global material added to in-use stocks amounted to 30 Gt in 2011. Based on the geographical distribution, 46% corresponded to material accumulated in China, 24% in high income regions, 21% in upper middle and middle income economies, and 10% in lower middle and lower income regions. On average, 4.3 t/cap of material were accumulated worldwide. The per capita values are almost two time higher for high income economies, which average 7.0 t/cap. With the exception of China (10.4 t/cap), upper middle income countries averaged 3.0 t/cap. Furthermore, the values for lower middle and lower income economies averaged 1.2 t/cap. Regarding material type, material inflows to in-use stocks comprised 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%). At sectoral level, for example, construction sector comprised around 90% of non-metallic minerals, which highlights the relevance of implementing circularity interventions for the construction sector.

Moreover, the geographical, material type, and sectoral distribution allow us to identify which of the 4 circularity interventions (from Chapter 2) can be applied for an effective management of the material inflows to in-use stocks. Resource efficiency and product lifetime are suitable interventions in the short-term because new stock additions can be designed in way that requires less input per unit output as well as prolonging product lifetime with access to repair and maintenance. Closing supply chains and residual waste management can be implemented in the long-term because the current stock additions will become waste in the future, which implies that the amount of waste from previous in-use stocks can be management through strategies that enhance the waste recovery and recycling.

6.2.4. RQ4. *What are the expected macroeconomic, social, and environmental impacts of circularity interventions at national and global level?*

This question was addressed by a meta-analysis of prospective studies that assess the potential changes in GDP, employment, and carbon emissions caused by a circularity transition. The core idea was to find a consensus on the magnitude of the macroeconomic, social, and environmental impacts of circularity intervention at macro scale. In Chapter 5, over 300 circular economy scenarios (CESs) from 2020 up to 2050 were reviewed and harmonized to perform a statistical analysis that allows us to determine whether circularity interventions could create a ‘win-win-win’ situation in terms of macroeconomic, social, and environmental impacts.

Considering the CESs for 2030, circularity interventions could generate incremental changes in GDP (median (mdn) = 2.0%; interquartile range (IQR) = [0.4–4.6]%) as well as job creation (mdn = 1.6%; IQR = [0.9–2.0]%). Furthermore, changes in CO_2 emissions could be more substantial (mdn = -24.6%), but values are largely spread (IQR = -[34.0–8.2]%). A correlation analysis showed that there is a positive relation between GDP and job creation, and a negative relation between these socioeconomic indicators and CO_2 emissions suggesting that a circularity transition could lead to 'win-win-win' situation (see table 5.2).

Chapter 5 also discussed the 3 main modelling features applied in CESs: resource taxes, technological and consumption pattern changes. Resource taxes (e.g. raw material taxes) were used by the modellers to assess the impacts of economic incentive on reducing material extraction. Technological changes were modelled by changes in production costs to reflect material efficiency improvements in specific industries. Changes in consumption patterns were introduced into the models by reducing the amount of goods or services for final demand due to product lifetime extension and sharing economy schemes. According to the reviewed literature, these modelling features yielded the greatest changes in GDP, employment, and CO_2 emissions.

On the basis of these answers on the research questions, we now can reflect on the main research question of this thesis (in section 1.5*): Is circular economy a suitable paradigm to ensure a global socio-economic and environmental sustainability?* We could see through each chapter that material circularity plays an important role for a sustainable resource management. However, a circular economy by itself will not be enough to address global sustainability issues, for example, climate change mitigation, the illusion of an infinite economic growth and wellbeing. We saw that the current amount of waste available for recovery and recycling is not enough to satisfy the demand of new goods and services. This is because global material inflows to in-use stocks are significantly higher than the materials removed from in-use stocks. As the global in-use stocks still growing, it becomes crucial to implement strategies in which stock additions are designed for longevity, where product's design facilitates the maintenance and recovery of materials added to in-use stocks in the future (e.g. by repairing and allowing products to be dissembled effectively for refurbishing or recycling).

Even if the global economy would have had an equilibrium between inflows and outflows from in-use stocks, half of extracted materials are used for food and energy purposes which by nature are dissipative uses. This means that it is still required to extract a significant amount of materials to satisfy human needs. Hence for biotic materials and energy flows, material circularity (as defined in this thesis) has a limited contribution to circularity in mass terms. This is because biotic and energy flows are usually dissipated in the environment (as dissipative emissions from combustion and biological nutrients after food consumption). The dissipative use of fossil energy flows should be reduced and even eliminated by a transition to renewable energy sources. For biotic materials, recovery of biological nutrients is the key to circularity, and opportunities for recovery at their highest value-added are still missed (EMF, 2013; Haas et al., 2020). Reduction of food waste is another option to reduce biotic material losses (EMF, 2013). To achieve a sustainable resource use worldwide, it would hence be required the integration of other existing strategies for food and energy systems together with circularity interventions.

In general, implementing the material circularity paradigm seems most pressing for high income countries and fast-developing economies (such as China). This is because these regions, according to Chapter 3, present the highest circularity gaps. The gap as defined in Chapter 3 forms the potential supply of secondary materials for a circularity transition at present. In contrast, middle and lower middle income economies even more than high income countries are still in a phase of investment growth that drives material accumulation, a situation that also still is true for China. Thus, the *current potential* material circularity of such investment-driven countries is limited as there is less supply of secondary materials available at the present. Such countries that now accumulate high amounts of materials in the form of in-use stocks, face the following challenge. First, they should build such in-use stocks with minimal resource use and carbon emissions. But equally important, they should design their in-use stock prepared for circularity, so that the product lifetimes of stock additions are maximized, and components and materials from in-use stocks removals can be easily re-used at the end of life of such stocks. This reflects the fact that countries in different phases of economic development may apply slightly different strategies for realising a circularity transition.

6.3. Limitations and further research

The development of the MR-HIOT EXIOBASE as applied in this thesis brings a significant step forward to assessing circularity interventions compared with traditional IOTs. Most of the EEIOA-based studies performed until now use monetary IOTs to assess the impacts of circular economy policies (see Chapter 2). At the same time, circular economy targets usually are expressed in mass terms (e.g. reducing the amount of waste generation) (EC, 2020). To avoid a disconnection between monetary and physical values of waste flows and other material flows, the empirical analyses in Chapter 3 and 4 were assessed in a hybrid-unit IOTs (i.e. MR-HIOT EXIOBASE) that expresses material flows in mass terms.

The MR-HIOT EXIOBASE is the first global, multiregional IOT that provides a physical rather than monetary representation of global value chains (Merciai & Schmidt, 2018). Compared to the use of traditional monetary global IOTs, the MR-HIOT EXIOBASE constitutes a better basis for assessing the physical structure of the global economy as well as the options and impacts of circularity interventions. Being the first of its kind, it is not surprising that further improvements of this MR-HIOT EXIOBASE are possible. Based on the discussion from Chapter 2 to 5, the following sub-sections discuss the thesis limitations and further research of six main aspects: data resolution, waste accounts, time series, stock accounts and stock-flow modelling, dynamic modelling, and data uncertainty.

6.3.1. Data resolution

The MR-HIOT EXIOBASE has a resolution of 163 sectors and 200 product categories per country, which is higher than other (monetary) global IOTs available. At the same time, even such a detailed sector resolution implies that various individual materials and products are aggregated to a single product group – an IOT simply is not meant to discern the tens of thousands of products and materials used in the global economy. For example, the non-metallic minerals category does not distinguish between concrete, sand, or aggregates, which have different energy requirements and environmental impacts (Wiedenhofer et al., 2019). Another example is the re-use of components (e.g. copiers), in which it would require having specific information on the production and use, rather than an aggregated product groups (e.g. electrical and electronic equipment).

A disaggregation of material and economic sectors can contribute to a detailed understanding of specific material types and how can be used in a circular manner. Although increasing resolution of the MR-HIOTs is desirable, it is important to notice that the disaggregation of material and economic sectors is restricted because the lack of data, which is particularly a challenge for waste accounting (Salemdeeb et al., 2016). In this matter, a possible alternative is the use of hybrid models using life cycle inventories (LCI) data. The LCI can be integrated into the MR-HIOT to provide the missing information for disaggregating specific sectors. For example, some researchers have developed linkages between LCI and integrated assessments models (IAMs) resulting in detailed stock-flow models for use sectors, such as housing, utility buildings and the transport sector (see, for example, Deetman et al., 2020; Mendoza Beltran et al., 2020). In a similar way, MR HIOTs could be hybridized with LCI data.

6.3.5. Improving waste accounts

For waste accounting in the MR-HIOT, there are some data improvements that should be addressed in future assessment of material circularity. First, as already discussed other economic activities, waste treatment sectors are quite aggregated, discerning just some 15 treatment options such as re-processing of secondary construction material into aggregates, and recycling of bottles by direct reuse. This limits the analysis of specific waste flows, which is also related to the level of resolution for waste accounts. Second, waste accounting can be underestimated due to informal or illegal waste are not available in the current accounting system (Tisserant et al., 2017). Third, there is currently a disconnection of international waste trade, where it is not possible to distinguish the international trade of waste for identifying the effect of international circularity interventions.

6.3.2. Time series

The MR-HIOT EXIOBASE is currently available for one year (i.e. 2011). This does not allow to assess the evolution of inflows and outflow in the global economy, which could provide more insights about the current state of material circularity (Haas et al., 2020; Krausmann et al., 2017). One of the reasons is the lack of time series in the MR-HIOT EXIOBASE as its construction requires a significant amount of effort for data collection and harmonization (Schmidt & Merciai, 2017). With the first MR-HIOT version and its developed procedures, we might expect that future MR-HIOTs versions would be available for multiple and more recent years. For now, it is still important to consider the construction of time series for the MR-HIOT to contribute to the development of assessing the material evolution in the global economy. This will also allow us to monitor the waste generation from old in-use stocks and the circularity gap through time per each country and region.

6.3.3. Integrating stock accounts and stock-flow modelling

At this moment, EEIOTs (including the MR-HIOT EXIOBASE) represent capital formation in a single year as column of gross fixed capital formation (GFCF) in final demand. Only a few studies allocated GFCF to production sectors and final demand by integrating capital formed in a specific year via an investment matrix and/or endogenizing GFCF in the intermediate demand matrix (Södersten et al., 2018a, 2020). EEIOTs hence usually do not give insight in the amount of fixed capital basis per sector of production and in use with final consumption, nor in which year elements of this fixed capital was produced. In environmental footprint studies, the impacts of capital formation usually are not allocated to specific final demand categories. At the same time, we saw in Chapter 3 that around 40% of the material extraction globally ends up as in-use stocks, which comprise fixed capital formation in the form of buildings, infrastructure, transport equipment, and other durable products.

As shown by Krausmann et al. (2017, 2020) and Södersten et al. (2018b), the material use and environmental impacts of capital formation are significant and, thus, it is crucial to understand where fixed capital is used and how to design the future capital formation for material circularity. Furthermore, most of the studies in Chapter 5 do not consider the amount of investment required to implement circularity interventions. This means that circularity interventions have been modelled as zero-cost policies, which could imply an overestimation of the economic gains of circular economy policies. To do so, further research should be focused on integrating the stock-flow aspects into the MR-HIOT system. Such stock-flow models incorporated in MR-HIOT also would enable to understand the amount of fixed capital is required to obtain certain production level and value added. Insight in stock age-cohort (or vintage models) is also essential to estimate capital formation and depletion, and in relation the volumes at specific times in future of outflow of waste (as shown, for example, by Deetman et al., (2020).

6.3.4. Dynamic modelling

The current static nature of the MR-HIOT limits the assessment of material circularity. This is because a static model does not permit to evaluate properly the impact of circularity interventions on the use phase of products, transition stages, and material stock-flow management in the long term (Sigüenza et al., 2020).

As the global material inflows and outflows occur in a dynamic system, thus, the use of dynamic input-output and material flow models can contribute to enhance the understanding of material circularity (Duchin et al., 2016; Wiedenhofer et al., 2019). For example, dynamic modelling could improve the circularity gap metric by considering the dynamic of the inflows and outflows to in-use stocks. Furthermore, the use of computable equilibrium (CGE) models brings a way to assess circularity considering the economic dynamics, which can be linked in the MR-HIOT for further modelling development (OECD, 2017; Pauliuk et al., 2017). Several CGE models present a recursive-dynamics (i.e. solving one period at a time), however, there are advance CGE models that enable a dynamic computation (Winning et al., 2017). The latter ones can be used as basis to incorporate dynamic modelling using the coefficient from the MR-HIOT, allowing to assess a more comprehensive dynamic of the macroeconomic, social, and environmental implications of a circularity transition.

A dynamic modelling into the MR-HIOT can enable the assessment of relevant modelling features. For example, as shown in Chapter 5, there is a lack of quantitative analysis of the potential rebound effect of circularity, where the economic savings from circularity interventions could be re-expected in goods or services that generate negative social and environmental impacts (Zink & Geyer, 2017). Assessing the rebound effect of circularity interventions should be considered by future modellers to identify the cost-effectiveness of circular economy policies. In this matter, IAMs and dynamic CGE models have been used to assess dynamic rebound effects (for example, IRP, 2019; Pauliuk et al., 2020), in which the MR-HIOT can be integrated to further data development.

6.3.6. Data uncertainty

How accurate the MR-HIOT represents reality is unknown at the present. This is a general problem for global MRIOTs, which are constructed from a large number of data sets that need to be harmonized (de Koning, 2018). For instance, the MRIOT EORA presents an uncertainty analysis in which each datapoint contains a rough estimate of its standard deviations (Casella et al., 2019; Giljum et al., 2019). To ensure that global trade is balanced, practitioners building MRIOTs usually have to override to some extent data provided via national statistics.

Until now, the uncertainty analysis of global MRIOTs mainly focused on evaluating what factors caused differences in the calculation of environmental footprints between different global MRIOTs (Giljum et al., 2019; Owen et al., 2014; Tukker et al., 2018) . As the MR-HIOT EXIOBASE is a novel accounting system, there were some data validations under the assumption that the aggregated magnitude of material inflows and outflows should match with previous global MFA studies (see supporting information in Chapter 3 and 4). However, there is no existing uncertainty analysis of the database. This can be done by applying previous approaches for uncertainty analysis of IOTs (Lenzen et al., 2010). As discussed in Chapter 2, uncertainty analysis is a recurrent issue of data reliability and validation within EEIOA community, which requires further research to guarantee data quality for the assessment of material circularity.

6.4. Final remarks

A macro-level assessment of material circularity provides a starting point to discuss the key aspects to achieve a successful circularity transition on a macro scale, which will be essential for achieving a sustainable resource management. The following sub-sections show some final reflexions about the research and policy implications of this thesis.

6.4.1. Research implications

The development of EEIOA has contributed to the assessment of material circularity in the past 3 decades. We saw how the EEIOA application has evolved through time, and now it brings a consistent and comprehensive framework to evaluate the impacts of circular economy policies. Although the current improvements, the EEIOA and other macro-economic approaches (e.g. CGE models) still require a further development in terms of data, modelling features, and a suitable framework to assess trade-offs. As explained by de Koning (2018), there is still a need to use models where the linkages between socio-economic metabolism and ecological systems are considered, which is also a called for the improvement of IAMs. As researchers motivated by pursuing a resource-efficient society, we should aim to address the current questions about material circularity in a way that reflect the net impacts of a circularity transition. Thus, it is important to incorporate the current modelling features that limit current analyses, such as investment, rebound effect and potential trade-offs between macroeconomic, social, and environmental impacts. Overall, our research contribution would rely on whether the findings could guide policy makers on achieving sustainable development goals. I consider that even with the current data limitations, it is still possible to provide a 'bird's-eye view' on material circularity that allows us to understand the big picture, and brings a quantitative perspective that can support decision makers in visualizing sustainable narratives for the upcoming decades.

6.4.2. Policy implications

There are important points to consider depending on each country and region, as they present different material profiles which can be improved through multiple circularity interventions. Considering the main research: Is circular economy a suitable paradigm to achieve an economic and environmental sustainability on a macro scale? We saw that a circular economy could contribute to macroeconomic, social, and environmental benefits; but it will not be enough to achieve sustainable development goals along. This does not mean that material circularity is not need it. In fact, if we consider new low-carbon technologies required to mitigate climate change and to use resources efficiently, the design for circularity can avoid the potential negative socioeconomic and environmental impacts of new technologies. On the other hand, a circularity transition might not create a radical transformation of resource use and its impacts in the upcoming decade, instead it is likely to be an incremental transition. Based on this, I consider that material circularity is not an enabler of sustainability, but rather a paradigm that offers a way to 'ignite' a sustainable resource management in the future.

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