A macro level of assessment of material circularity

Aguilar Hernandez, G.A.

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GLENN A. AGUILAR HERNANDEZ

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“Only those who attempt the absurd will achieve the impossible.”

M.C. Escher (1898-1972)

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Chapter 1

General introduction

1.1. Natural resources, and the challenges of sustainable resource management

There is an undoubtable strong link between human welfare and nature. To satisfy fundamental human needs, such as subsistence and protection (Ekins & Max-Neef, 1992), we rely on natural resources. These are the living (i.e. biotic) and nonliving (i.e. abiotic) parts of the physical environment that serve a need, are useful and available at certain cost (Spellman & Stoudt, 2013). Food, water, air and land are some of the natural resources without which no human life is possible. As such, there is a major interest in having access to these resources without threatening its future availability. In this context, sustainable development is the concept that describes one of the humankind's main goals: satisfying the current human needs without compromising the needs of future generations (Brundtland & Khalid, 1987). To achieve a sustainable resource management, two of the main challenges are disruptive events, and the increase of resource extraction.

Disruptive events are disturbances or problems that interrupt an activity or an event (Okuyama et al., 1999). Such events can be caused by natural disasters (such as earthquakes and hurricanes), and socioeconomic shocks (e.g. political revolution and financial crisis). A disruptive event can cause a risk for resources availability, particularly in current times where the global economy is highly interconnected, which enables a greater risk to propagate disruptive supply chains (OECD, 2011). A clear example is happening at the time of writing this dissertation, where we are facing an unprecedented disruptive event: the COVID-19 outbreak (WHO, 2020). This pandemic has a direct effect on the global economy, disrupting supply chains and affecting the availability and accessibility of certain resources. For example, as one of the biggest manufacturers worldwide, China has decreased in the production and trade of manufactured goods (e.g. electronics, pharmaceutical and medical devices), which means a risk for supply chains in multiple countries that are net importers (Hedwall, 2020; OECD, 2020b). Although the overall impacts of COVID-19 outbreak on resource use will be seen in the near future, it remains that disruptive events might occur, and the importance of considering a sustainable resource management that provides resilient supply chains (IRP, 2020; OECD, 2020a).

Resource extraction refers to the use of natural resources for economic activities such as agriculture, mining, and drilling activities (UNEP, 2011). In the past century, the degree of resource extraction has significantly increased worldwide. For example, the global extraction of biomass, fossil fuels, non- and metallic minerals increased from 7 Gigatonnes (Gt) in 1900 to 89 Gt in 2015 (Krausmann et al., 2018). Furthermore, resource use and environmental impacts are usually linked to three main drivers: population growth, affluence, and technological development (Giljum et al., 2015; UNEP, 2016). However, there are limits to resource extraction. As we live in a world with finite natural resources, it is clear that infinite resource extraction is not possible, which also implies that there are also limits to economic growth (Meadows & Randers, 1974). Moreover, the current level of resource extraction constitutes a strong pressure on ecosystems and leads to the depletion of natural resources (Bringezu et al., 2009). For example, there are linkages between resource extraction and climate change, where the extraction and production of materials (e.g. concrete, steel, and plastics) contribute to around 25% of global greenhouse gases emissions (UNEP, 2019). As a feedback effect, the impacts on climate change reduce the availability and accessibility of resources in the long term (Lampert, 2019).

Considering the impacts of increasing resource extraction and disruptive events on socioeconomic and environmental sustainability, there is a need to explore sustainable solutions that allows us to reduce the risk of disruptive supply chains as well as preserving natural resources to satisfy future human needs (Tercero Espinoza et al., 2020; Vita et al., 2018). To achieve a sustainable resource use, several models have been studied to understand how to decouple environmental pressures and economic activities by looking at ways to create a resource-efficient society (Meyer et al., 2018; Schandl et al., 2016; UNEP, 2011). The following section will explain one of the current approaches to address the challenges of a sustainable resource management.

1.2. Circular economy and circularity interventions

One of the most attractive approaches towards a resource-efficient society is the circular economy. This paradigm aims to reduce resource extraction as well as waste flows by retaining materials into the economy (EMF, 2013; Lieder & Rashid, 2016). The concept has been proposed by Pearce and Turner (1990) as a way to transform the traditional open-ended economy (or linear economy) into an ongoing closed-loop material system. Since then, the circular economy concept has increased its popularity in sustainability research, policy and business fields (Bocken et al., 2017; Winans et al., 2017). For instance, a literature search on Web of Science using the term "circular economy" yielded 171 records between 1990 and 2014, and 3147 records between 2015 and 2019. This shows an increase of 18 times in the past 5 years regarding circular economy literature.

The circular economy concept is based on three main principles (EMF, 2015; Ghisellini et al., 2016):

1) to reduce waste by using waste flows as inputs for other economic activities;
2) to optimize material loops by prolonging product lifetime, reusing, recycling, and other resource recovery activities; and
3) to provide a restorative environment by decreasing material extraction and its environmental impacts.

It is important to notice that these principles are not completely new, and the circular economy principles result from a plethora of school of thoughts. For example, industrial ecology, performance economy and cradle-to-cradle are prior concepts that have been exploring ways to achieve material circularity (Frosch & Gallopoulos, 1989; Geissdoerfer et al., 2017; Stahel & Clift, 2015). However, several researchers point out that one of the novelties of the circular economy concept is that it focuses on implementing strategies from a business perspective (see, for example, Bocken et al., 2017; Moreno et al., 2016; Stahel, 2012). This follows the idea that a circular economy can be seen as an economic system that is resilient to potential disruptive events, which enables economic and environmental sustainability (Kirchherr et al., 2017).

Based on the circular economy principles mentioned above, there are actions or processes that lead material circularity and a sustainable resource use (Bocken et al., 2016; EMF, 2013). These actions or processes are called circularity interventions (Donati et al., 2020). Several researchers and practitioners have grouped circularity interventions in multiples ways to facilitate their assessment, for example, using 9 R's strategies (e.g. Reuse, Repair, Recycling, etc.) framework (Potting et al., 2017) and resource use archetypes (Bocken et al., 2016; EMF, 2013).

In this thesis, circularity interventions are classified in 4 main groups: residual waste management, closing supply chains, product lifetime extension, and resource efficiency. This classification provides a comprehensive overview of circularity interventions on a macro scale, which is based on circular economy strategies proposed by the Ellen MacArthur Foundation (2013), Bocken et al. (2016), and Kirchherr et al. (2017). First, residual waste management refers to post-consumption activities where the resources are disposed outside the economy, which includes waste treatment activities such as incineration, landfilling and recycling activities. Second, closing supply chains are interventions to reintroduce materials on multiple levels of a supply chain through actions such as component re-use, product repurposing and refurbishment. Third, product lifetime extension related to slowing-down resource use and extending product lifetime by designing for longevity, repair and maintenance. Finally, resource efficiency includes actions in which material use is optimized by using less material inputs per unit outputs. Chapter 2 will bring further examples of each circularity intervention category.

Circularity interventions and their implementation have become an important aspect of sustainability policies, which are focused on resource efficiency strategies as policy measures to provide economic and environmental benefits (Andersen, 2007; Geissdoerfer et al., 2017). For example, the European Union and China have proposed action plans to promote material circularity in the upcoming decades (EC, 2020; Geng et al., 2012). Such action plans imply that circularity interventions are considered suitable measures to enable a sustainable resource use on national and multinational levels (WEF, 2014).

1.3. A global picture of material circularity

A global perspective on material circularity is crucial to understand which policy measures can be implemented to promote a widespread adoption of circularity interventions, i.e. a circularity transition (Geng et al., 2012a; McDowall et al., 2017). This has led to several studies that assess the global material inflows and outflows, providing a global picture of resource use and its environmental implications (Murray et al., 2015).

For example, Haas et al. (2015) brought an overview of the circularity degree of the global economy in 2005. The authors showed that around 45% of resources are used for food and energy purposes, and almost 30% of extracted materials are accumulated as capital formation (or in-use stocks) in the form of buildings, infrastructure, and products with long lifespan.

Furthermore, they quantified the degree of circularity as the ratio between waste recycling and domestic material input (i.e. the sum of domestic material extraction and imports), which represented less than 5% of global material circularity worldwide for the period.

In a similar way, Cullen (2017) measured the recycling rate of particular material groups such as aluminium, concrete, paper, plastic and steel. The author established a mathematical relation between the recycling rate of these material and the energy requirements for raw material extraction and secondary material (i.e. recovered or recycled materials) production, which is called material circularity index. At global level, the values of material circularity index varied from 4% (for paper) to 20% (for aluminium), suggesting that there is an 80-96% of materials that can be used for recovery or recycling.

Shortly after, de Wit et al. (2018) introduced the circularity gap metric as an indicator of how much secondary materials are required in order to replace the global material extraction of one period. To do so, they quantified the share of recovered or recycling materials compared with the total material extraction in 2015. Their results showed that the global material recovery and recycling represented less than 10% of the total material inputs, which leads to a theoretical circularity gap of 90% materials available for recovery.

Although the previous studies provided an overview of global material inflows and outflows as well as the potential for material circularity, there is still a lack of understanding on how a global circularity transition might look like (Pauliuk, 2018; WEF, 2014). Likewise, the magnitude of the potential economic, social, and environmental implications of material circularity at global level is not clear (Wiebe et al., 2019; Woltjer, 2018). These issues will be discussed in detail in Chapter 3, 4 and 5. Moreover, a growing body of literature has explored which methods can be applied to assess the impacts of a circularity transition in a systematic way (Elia et al., 2017; Potting et al., 2017). The next section will review three of the main methods used for the impact assessment of a circularity transition based on industrial ecology tools.

1.4. Assessing material circularity

To perform sustainability assessments of material circularity it is first necessary to analyze the material and energy flows used by society (Graedel & Lifset, 2016; Pauliuk & Hertwich, 2016). Regarding the assessment of material flows in specific socioeconomic systems and their environmental impacts, there are three main method used in Industrial Ecology (Pauliuk et al., 2017): life cycle assessment (LCA), material flow analysis (MFA), and environmentally extended input-output analysis (EEIOA). The rest of the section will review these methods in the context of material circularity.

LCA is an approach to compile and analyze the inflows, outflows as well as environmental impacts of the production of goods and services thought its life cycle (Heijungs & Guinée, 2012). The LCA framework has been applied to assess the potential environmental impacts of circular economy activities, for example, how recycling and remanufacturing processes would influence the reduction of carbon emissions compared with the production of goods from raw materials (see, for example, Broadbent, 2016; Liu et al., 2014). LCA studies are mostly focused on attributional aspects, in which it is common to compare environmental impacts of a product from business as usual model with an alternative product from a circular economy business model (Haupt & Zschokke, 2017; Niero & Olsen, 2016). Thus, this approach is useful to analyze environmental impacts at product level (or micro level perspective).

MFA is a well-known method to assess the material flows throughout economic activities, which provides a consistent framework for tracing the use of materials as well as emissions and waste generation from an economy (Eurostat, 2013; Graedel, 2019). Several MFA studies have been used to evaluate the level of material circularity at country and regional scales (Jacobi et al., 2018; Kovanda, 2014; Nuss et al., 2017; van Eygen et al., 2017). The use of MFA approach on material circularity has led to the identification of the degree of recycling on different material types, for example, metals (e.g. copper and steel) (Dong et al., 2019; Gorman & Dzombak, 2020; Miatto et al., 2017; Pfaff et al., 2018; Zeng et al., 2018) and construction materials (e.g. concrete, sand, and aggregates) (Deetman et al., 2020; Marinova et al., 2020; Schiller et al., 2017; Wuyts et al., 2019). Furthermore, the MFA approach has led to the development of a framework for monitoring material circularity with applications at meso- (e.g. industries or cities) and macro scales (e.g. countries or worldwide) (Jacobi et al., 2018; Mayer et al., 2018).

EEIOA results from an integration of environmental accounting system with economic input-output tables (IOTs), which represent the economic transactions between economic sectors and final demand (e.g. households and government expenditures) (Eurostat, 2008; Miller & Blair, 2009). The main advantage of EEIOA is that this approach takes into account the size and structure of an economy, providing a systems where the impacts of circularity transition can be analyzed on a macro scale (Lenzen & Reynolds, 2014; Munksgaard et al., 2005). A few EEIOA studies have assessed the potential economic, social, and environmental impacts of circularity interventions in multiple countries and regions (Donati et al., 2020; Duchin, 1992; Iacovidou et al., 2017). Furthermore, EEIOA has been used to assess the degree of material circularity through the application of IOTs in hybrid (i.e. combining monetary, physical, and energy) and physical units (Beylot & Villeneuve, 2015; de Wit et al., 2018). This application of EEIOA has led to the development of advanced EEIOA methods for assessing material circularity (Çetinay et al., 2020; Donati et al., 2020). For example, Nakamura and Kondo (2009) used the EEIOA approach to develop an accounting system that provides a connection between economic activities and waste generation (i.e. waste input-output tables), in which it is possible to analyze the environmental impacts of changes in waste treatment activities (e.g. incineration, landfilling or recycling industries). Thus, EEIOA can be used to evaluate the potential economic, social, and environmental impacts of circularity interventions at macro scale.

Overall, EEIOA presents a consistent framework to assess the economic social, and environmental implications of circularity interventions on a global level. There are other macroeconomic approaches that serve this purpose, such as computable equilibrium models and integrated assessment models (Best et al., 2018; de Koning, 2018; McCarthy et al., 2018). These models will be addressed in Chapter 5. For now, this thesis focuses on the application of EEIOA for understanding the macro level impacts of material circularity.

1.5. Problem statement, objectives, and research questions

In section 1.1, we saw that there is a current societal need to achieve a sustainable resource management that provides resilient supply chains in the long term. Furthermore, section 1.2

introduced the concept of circular economy and circularity interventions as measures that enable the sustainable resource management. However, as mentioned in section 1.3, there is currently a poor understanding of the magnitude of the economic, social and environmental impacts of the implementation of circularity interventions, which raises the main research question: *Is circular economy a suitable paradigm to ensure a global socio-economic and environmental sustainability?*

The main objective of this thesis is to assess whether circularity interventions could contribute to a sustainable resource management worldwide, and explore which circularity interventions could lead to a cost-effective circularity transition at the macro scale.

This thesis has chosen EEIOA as its main analytical framework to address the main objective. As mentioned in section 1.4, EEIOA brings a consistent, economy-wide framework to evaluate the macro level impacts of a circularity transition. EEIOA inherently covers economic aspects (e.g. the creation of value added), and social aspects (e.g. the amount of jobs and wages by industry). In contrast with MFA and LCA, the EEIOA method can hence be used to assess macroeconomic, social, and environmental impacts of circularity interventions in a comprehensive way. MFA also covers the economy-wide view, however, this method lacks of the economic and social aspects (Krausmann et al., 2017, 2018). LCA is suitable for circularity assessments at detailed product level, but is limited in covering the entire economy (Sigüenza et al., 2020) . This thesis focuses on the assessments from a macro-economic view and, thus, EEIOA is used as a starting point for this research.

In relation to the choice of EEIOA as main method, there are several aspects in which the assessment of material circularity can be explored and improved. This thesis focuses on four sub-goals required to address the main research objective. First, there is a need to understand how to apply EEIOA in the assessment of circularity interventions, and what guidance EEIOA might provide for circularity improvements. Second, it is essential to investigate how much waste is available that can be used as secondary materials for a global material circularity. Third, there is a need to identify where materials are accumulated in the global economy for the adoption of material circularity. Fourth, it requires to evaluate what could be the potential macroeconomic, social, and environmental impacts of material circularity. The following are specific research questions to address the sub-goals:

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

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

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

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

1.6. Reading guidelines

The present section describes the structure of this thesis, and provides a reading guideline. Figure 1.1 shows an outline of the dissertation in relation to each research question (RQ).

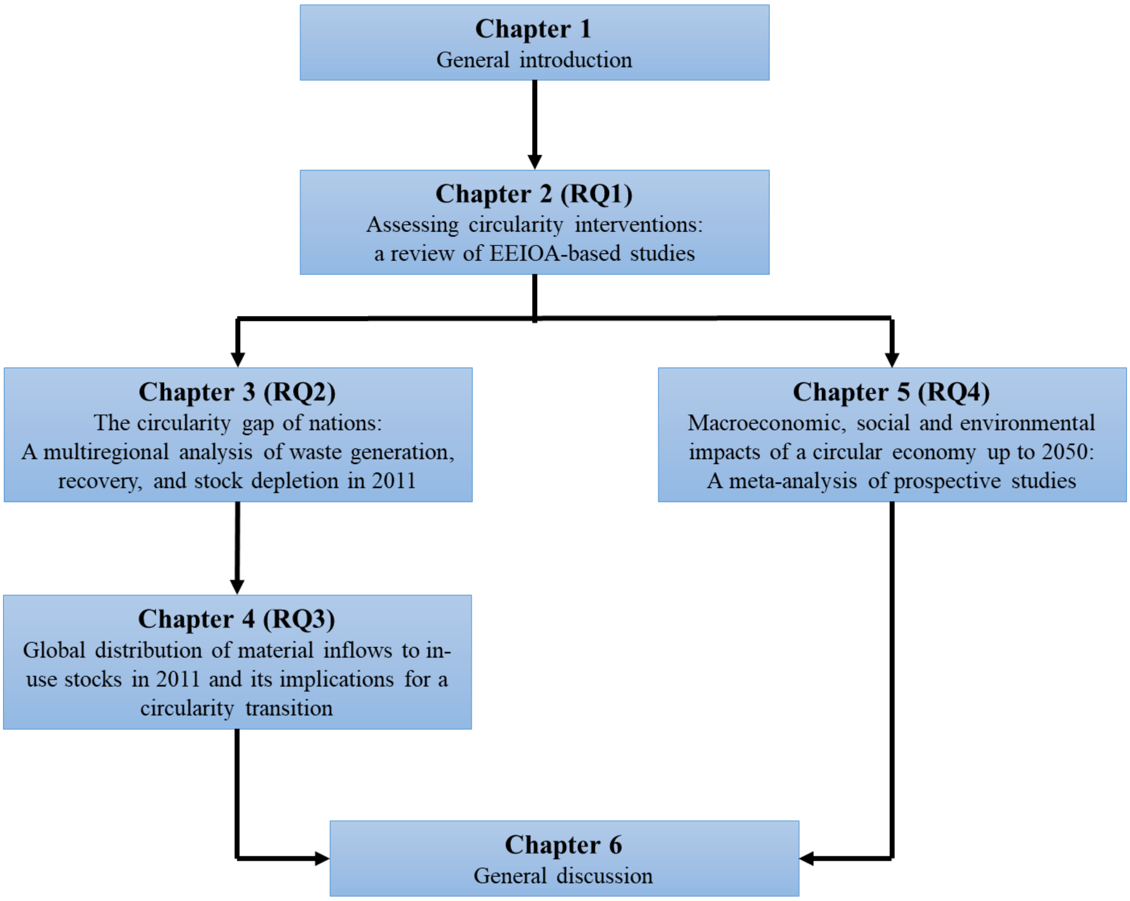

Figure 1.1. Outline of this dissertation linked to each research question (RQ)

From figure 1.1, Chapter 2 brings the state of the art of EEIOA-based studies that assesses the impacts of circularity interventions in the last 30 years, which answers RQ1. This chapter also offers a novel framework that illustrates the further development and best practices of EEIOA method for assessing circularity interventions.

Chapter 3 explores the concept of the circularity gap, and establishes a new metric that quantifies the amount of unrecovered waste available for recovery and recycling in a period. The metric is applied to estimate the circularity gap of 43 countries and 5 rest of the world regions. This chapter addresses RQ2, and brings into discussion how to apply circularity interventions for reducing the circularity gap of a country or region.

Chapter 4 begins with the results of Chapter 3, where it is highlighted the role of material accumulated in society for a circularity transition. Thus, Chapter 4 examines the global distribution and composition of material accumulated as in-use stocks (e.g. building, infrastructure, and transport equipment) in one period, which addresses RQ3. Furthermore, this chapter discusses which circularity interventions can be implemented in the short- and long-term to provide a cost-effect resource management of material inflows to capital formation.

Chapter 5 focuses on RQ4, and explores there is a consensus among existing literature regarding the potential impacts of circularity on changes in gross domestic product, job, creation and carbon emissions in the upcoming decades. By performing a meta-analysis on circular economy scenarios, this chapter brings insight into the magnitude of the macroeconomic, social, and environmental impacts of a circularity transition.

Finally, Chapter 6 presents a general discussion based on the RQs as well as final remarks, which includes limitations and further research.

1.7. References

Andersen, M. S. (2007). An introductory note on the environmental economics of the circular economy. *Sustainability Science*, *2*(1), 133–140. https://doi.org/10.1007/s11625-006-0013-6

Best, A., Duin, L., & Chelminske, M. (2018). *Macroeconomic and Societal Impacts of Mainstreaming the Circular Economy. Deliverable D5.3 Circular Impacts*.

Beylot, A., & Villeneuve, J. (2015). Assessing the national economic importance of metals: An Input-Output approach to the case of copper in France. *Resources Policy*, *44*, 161–165. https://doi.org/10.1016/j.resourpol.2015.02.007

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bocken, N. M. P., Olivetti, E. A., Cullen, J. M., Potting, J., & Lifset, R. (2017). Taking the Circularity to the Next Level: A Special Issue on the Circular Economy. *Journal of Industrial Ecology*, *00*(0), 1–7. https://doi.org/10.1111/jiec.12606

Bringezu, S., Sand, I. van de, Schütz, H., Bleischwitz, R., & Moll, S. (2009). Analysing global resource use of national and regional economies across various levels. In S. Bringezu & R. Bleischwitz (Eds.), *Sustainable Resource Management Global Trends, Visions and Policies* (1st ed., pp. 2–49). Taylor & Francis.

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT*, *21*(11), 1658–1665. https://doi.org/10.1007/s11367-016-1081-1

Brundtland, G. H., & Khalid, M. (1987). *Our common future*. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

Çetinay, H., Donati, F., Heijungs, R., & Sprecher, B. (2020). Efficient computation of environmentally extended input–output scenario and circular economy modeling. *Journal of Industrial Ecology*, 1–10. https://doi.org/10.1111/jiec.13013

Cullen, J. M. (2017). Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *Journal of Industrial Ecology*, *00*(0), 1–4. https://doi.org/10.1111/jiec.12599

de Koning, A. (2018). *Creating Global Scenarios of Environmental Impacts with Structural Economic Models* [Leiden University]. https://doi.org/ISBN: 978-94-90858-55-1

de Wit, M., Hoogzaad, J., Ramkumar, S., Friedl, H., & Douma, A. (2018). *The circularity gap report. An analysis of the circular state of the global economy. Technical Report*.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*, 104508. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104508

Donati, F., Christis, M., Tukker, A., Niccolson, S., Boonen, K., Koning, A. De, Geerken, T., Daniels, B., & Rodrigues, J. F. D. (2020). Modeling the circular economy in environmentally extended input – output A web application. *Journal of Industrial Ecology*, 1–15. https://doi.org/10.1111/jiec.13046

Dong, D., Tukker, A., & Van der Voet, E. (2019). Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *Journal of Industrial Ecology*, *23*(6), 1363–1380. https://doi.org/10.1111/jiec.12926

Duchin, F. (1992). Industrial input-output analysis: Implications for industrial ecology. *Proc. Natl. Acad. Sci.*, *89*, 851–855. http://www.pnas.org/content/89/3/851.full.pdf

EC. (2020). *Circular Economy Action Plan: For a cleaner and more competitive Europe*. https://ec.europa.eu/environment/circular-economy/

Ekins, P., & Max-Neef, M. (1992). *Real Life Economics* (London (ed.)). Taylor & Francis.

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

EMF. (2013). *Toward the circular economy. Technical Report*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

EMF. (2015). *Delivering the Circular Economy. A toolkit for policymakers*.

Eurostat. (2008). Eurostat Manual of Supply, Use and Input-Output Tables. In *Methodologies and working papers, Economy and finance*. https://doi.org/http://ec.europa.eu/eurostat

Eurostat. (2013). *Economy-wide Material Flow Accounts (EW-MFA) Compilation Guide 2013* (Issue July). http://ec.europa.eu/eurostat/web/environment/methodology

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for Manufacturing. *Scientific American*, *261*, 144–153. https://www.jstor.org/stable/10.2307/24987406

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy - A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of Cleaner Production*, *23*, 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of*

Cleaner Production, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giljum, S., Bruckner, M., & Martinez, A. (2015). Material footprint assessment in a global input-output framework. *Journal of Industrial Ecology, 19*(5), 792–804. https://doi.org/10.1111/jiec.12214

Gorman, M., & Dzombak, D. (2020). Stocks and flows of copper in the U.S.: Analysis of circularity 1970–2015 and potential for increased recovery. *Resources, Conservation and Recycling*, *153*(August 2019), 104542. https://doi.org/10.1016/j.resconrec.2019.104542

Graedel, T. E. (2019). Material Flow Analysis from Origin to Evolution. *Environmental Science and Technology*, *53*(21), 12188–12196. https://doi.org/10.1021/acs.est.9b03413

Graedel, T. E., & Lifset, R. J. (2016). Industrial Ecology's First Decade. In R. Clift & Angela Druckman (Eds.), *Taking Stock of Industrial Ecology* (pp. 3–20). SPRINGER. https://doi.org/10.1007/978-3-319-20571-7

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology, 19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Haupt, M., & Zschokke, M. (2017). How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. *The International Journal of Life Cycle Assessment*, *Vvea 2016*. https://doi.org/10.1007/s11367-017-1267-1

Hedwall, M. (2020, June 22). The ongoing impact of COVID-19 on global supply chains. *World Economic Forum*. https://www.weforum.org/agenda/2020/06/ongoing-impact-covid-19-global-supply-chains/

Heijungs, R., & Guinée, J. B. (2012). An Overview of the Life Cycle Assessment Method – Past, Present, and Future. In C. M.A. (Ed.), *Life Cycle Assessment Handbook; A Guide for Environmentally Sustainable Products* (pp. 15–42). Scrivener Publishing.

Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., & Williams, P. T. (2017). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production*, *166*, 910–938. https://doi.org/10.1016/j.jclepro.2017.07.100

IRP. (2020). *Building resilient societies after the COVID-19 pandemic*. https://wedocs.unep.org/bitstream/handle/20.500.11822/32287/COVIDIRP.pdf?sequence=1&isAllowed=y

Jacobi, N., Haas, W., Wiedenhofer, D., & Mayer, A. (2018). Providing an economy-wide monitoring framework for the circular economy in Austria : Status quo and challenges. *Resources, Conservation & Recycling*, *137*, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kovanda, J. (2014). Incorporation of recycling flows into economy-wide material flow accounting and analysis: A case study for the Czech Republic. *Resources, Conservation and Recycling*, *92*, 78–84. https://doi.org/10.1016/j.resconrec.2014.08.006

Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to out fl ows of wastes and emissions : The socioeconomic metabolism of the global economy , 1900 – 2015. *Global Environmental Change, 52*, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., & Fishman, T. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS*, *114*(8), 21–26. https://doi.org/10.1073/pnas.1613773114

Lampert, A. (2019). Over-exploitation of natural resources is followed by inevitable declines in economic growth and discount rate. *Nature Communications*, *10*(1419). https://doi.org/https://doi.org/10.1038/s41467-019-09246-2

Lenzen, M., & Reynolds, C. J. (2014). A Supply-Use Approach to Waste Input-Output Analysis. *Journal of Industrial Ecology*, *18*(2), 212–226. https://doi.org/10.1111/jiec.12105

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Liu, Z., Li, T., Jiang, Q., & Zhang, H. (2014). Life Cycle Assessment–based Comparative Evaluation of Originally Manufactured and Remanufactured Diesel Engines. *Journal of Industrial Ecology*, *18*(4), 567–576. https://doi.org/10.1111/jiec.12137

Marinova, S., Deetman, S., van der Voet, E., & Daioglou, V. (2020). Global construction materials database and stock analysis of residential buildings between 1970-2050. *Journal of Cleaner Production*, *247*, 119146. https://doi.org/10.1016/j.jclepro.2019.119146

Mayer, A., Haas, W., Wiedenhofer, D., Nuss, P., & Blengini, G. A. (2018). Measuring Progress towards a Circular Economy A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, *00*(0), 1–15. https://doi.org/10.1111/jiec.12809

McCarthy, A., Dellink, R., & Bibas, R. (2018). *The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches*.

Meadows, D. H., & Randers, J. (1974). *The limits to growth : a report for the Club of Rome's project on the predicament of mankind*. Pan Books.

Meyer, M., Hirschnitz-Garbers, M., & Distelkamp, M. (2018). Contemporary Resource Policy and Decoupling Trends — Lessons Learnt from Integrated Model-Based Assessments. *Sustainability*, *10*(1858), 1–28. https://doi.org/10.3390/su10061858

Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., & Tanikawa, H. (2017). Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, *127*, 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024

Miller, R. E., & Blair, P. D. (2009). *Input–Output Analysis: Foundations and Extensions* (Second edi). Cambridge University Press.

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability (Switzerland)*, *8*(9). https://doi.org/10.3390/su8090937

Munksgaard, J., Wier, M., Lenzen, M., & Dey, C. (2005). Using input-outpunt analysis to measure the environmental pressure of consumption at different spatical levels. *Journal of Industrial Ecology*, *9*(1), 169–186. https://doi.org/10.1162/1088198054084699

Murray, A., Skene, K., & Haynes, K. (2015). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*, 369–380. https://doi.org/10.1007/s10551-015-2693-2

Nakamura, S., & Kondo, Y. (2009). *Waste Input-Output Analysis: Concepts and Application to Industrial Ecology*. Springer.

Niero, M., & Olsen, S. I. (2016). Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements. *RESOURCES CONSERVATION AND RECYCLING*, *114*, 18–31. https://doi.org/10.1016/j.resconrec.2016.06.023

Nuss, P., Gian Andrea, B., Willi, H., Andreas, M., Viorel, N., & Pennington, D. (2017). *Development of a Sankey diagram of material flows in the EU economy based on Eurostat. Technical Report*. https://doi.org/10.2760/362116

OECD. (2011). *Future Global Shocks. Improving Risk Governance*. https://www.oecd.org/governance/48329024.pdf

OECD. (2020a). *A systemic resilience approach to dealing with Covid-19 and future shocks*. https://read.oecd-ilibrary.org/view/?ref=131_131917-kpfefrdfnx&title=A-Systemic-Resilience-Approach-to-dealing-with-Covid-19-and-future-shocks

OECD. (2020b). *Coronavirus: The world economy at risk*. https://www.oecd.org/berlin/publikationen/Interim-Economic-Assessment-2-March-2020.pdf

Okuyama, Y., Sonis, M., & Hewings, G. J. D. (1999). Economic Impacts of an Unscheduled, Disruptive Event: A Miyazawa Multiplier Analysis. In G. J. D. Hewings, M. Sonis, M. Madden, & Y. Kimura (Eds.), *Understanding and Interpreting Economic Structure* (pp. 113–145). Springer Berlin Heidelberg. https://doi.org/https://doi.org/10.1007/978-3-662-03947-2

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*(October 2017), 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change*, *7*(1), 13–20. https://doi.org/10.1038/nclimate3148

Pauliuk, S., & Hertwich, E. G. (2016). Prospective Models of Society’s Future Metabolism: What Industrial Ecology Has to Contribute. In R. Clift & Angela Druckman (Eds.), *Taking Stock of Industrial Ecology* (pp. 21–44). SPRINGER. https://doi.org/10.1007/978-3-319-20571-7

Pearce, D., & Turner, R. (1990). *Economics of natural resources and the environment*. Harvester Wheatsheaf.

Pfaff, M., Glöser-Chahoud, S., Chrubasik, L., & Walz, R. (2018). Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures. *Resources, Conservation and Recycling*, *139*, 205–218.

https://doi.org/10.1016/j.resconrec.2018.08.017

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product Chain*. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). *Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions*. https://doi.org/10.1016/j.jclepro.2015.06.100

Schiller, G., Müller, F., & Ortlepp, R. (2017). Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resources, Conservation and Recycling*, *123*, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007

Sigüenza, C. P., Steubing, B., Tukker, A., & Aguilar-Hernández, G. A. (2020). The environmental and material implications of circular transitions: A diffusion and product-life-cycle-based modeling framework. *Journal of Industrial Ecology*, 1–17. https://doi.org/10.1111/jiec.13072

Spellman, F. R., & Stoudt, M. L. (2013). *Environmental Science. Principles and Practices*. Scarecrow Press, Inc.

Stahel, W. R. (2012). *The business angle of a circular economy – higher competitiveness, higher resource security and material efficiency*. http://www.rebelalliance.eu/uploads/9/2/9/2/9292963/stahel_the_business_angle_of_a_circular_economy.pdf

Stahel, W. R., & Clift, R. (2015). Stocks and Flows in the Peformance Economy. In *Taking Stock of Industrial Ecology* (pp. 137–158). Springer International Publishing. https://doi.org/10.1007/978-3-319-20571-7

Tercero Espinoza, L., Schrijvers, D., Chen, W.-Q., Dewulf, J., Eggert, R., Goddin, J., Habib, K., Hagelüken, C., Hurd, A. J., Kleijn, R., Ku, A. Y., Lee, M.-H., Nansai, K., Nuss, P., Peck, D., Petavratzi, E., Sonnemann, G., van der Voet, E., Wäger, P. A., … Hool, A. (2020). Greater circularity leads to lower criticality, and other links between criticality and the circular economy. *Resources, Conservation and Recycling*, *159*, 104718. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.104718

UNEP. (2011). *Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel*.

UNEP. (2016). *Global material flows and resource productivity. Assessment report for the UNEP International Resource Panel*. http://www.isa.org.usyd.edu.au/about/16-00169_LW_GlobalMaterialFlowsUNEReport_FINAL_160701.pdf

UNEP. (2019). *Emissions Gap Report 2019*.

van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., & Fellner, J. (2017). Comprehensive analysis and quantification of national plastic flows: The case of Austria. *Resources, Conservation and Recycling*, *117*, 183–194. https://doi.org/10.1016/j.resconrec.2016.10.017

Vita, G., Hertwich, E. G., Stadler, K., & Wood, R. (2018). Connecting global emissions to fundamental human needs and their satisfaction. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aae6e0

WEF. (2014). Towards the Circular Economy : Accelerating the scale-up across global supply chains. In *World Economic Forum*. https://doi.org/10.1162/108819806775545321

WHO. (2020). *Practical actions in cities to strengthen preparedness for the COVID-19 pandemic and beyond An interim checklist for local authorities*. https://www.who.int/publications/i/item/WHO-2019-nCoV-ActionsforPreparedness-Checklist-2020.1

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825–833. https://doi.org/10.1016/j.rser.2016.09.123

Wuyts, W., Miatto, A., Sedlitzky, R., & Tanikawa, H. (2019). Extending or ending the life of residential buildings in Japan: A social circular economy approach to the problem of short-lived constructions. *Journal of Cleaner Production*, *231*, 660–670. https://doi.org/10.1016/j.jclepro.2019.05.258

Zeng, X., Zheng, H., Gong, R., Eheliyagoda, D., & Zeng, X. (2018). Uncovering the evolution of substance flow analysis of nickel in China. *Resources, Conservation and Recycling*, *135*, 210–215. https://doi.org/10.1016/j.resconrec.2017.10.014

Chapter 2

Assessing circularity interventions: A review of EEIOA-based studies

Based on: Aguilar-Hernandez, G.A., C.P. Sigüenza-Sanchez, F. Donati, J.F.D. Rodrigues, and A. Tukker. 2018. Assessing circularity interventions : a review of EEIOA-based studies. *Journal of Economic Structures* 7(14): 1–24. https://doi.org/10.1186/s40008-018-0113-3

Abstract

Environmentally extended input-output analysis (EEIOA) can be applied to assess the economic and environmental implications of a transition towards a circular economy. In spite of the existence of several such applications, a systematic assessment of the opportunities and limitations of EEIOA to quantify the impacts of circularity strategies is currently missing. This chapter brings the current state of EEIOA-based studies for assessing circularity interventions up to date and is organized around four categories: residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Our findings show that residual waste management can be modelled by increasing the amount of waste flows absorbed by the waste treatment sector. Closing supply chains can be modelled by adjusting input and output coefficients to reuse and recycling activities and specifying such actions in the EEIOA model if they are not explicitly presented. Product lifetime extension can be modelled by combining an adapted final demand with adjusted input coefficients in production. The impacts of resource efficiency can be modelled by lowering input coefficients for a given output. The major limitation we found was that most EEIOA studies are performed using monetary units, while circularity policies are usually defined in physical units. This problem affects all categories of circularity interventions, but is particularly relevant for residual waste management, due to the disconnect between the monetary and physical value of waste flows. For future research, we therefore suggest the incorporation of physical and hybrid tables in the assessment of circularity interventions when using EEIOA.

Keywords: circular economy, input-output analysis, waste management, recycling, closing loops, resource efficiency, product lifetime extension

2.1. Introduction

In the early 1990s, the concept of circular economy was proposed by Pearce and Turner (1990) as a model to transform the traditional open-ended economy into an ongoing closed-loop system from a material perspective. Since then, several scholars and practitioners have adopted multiple definitions for circularity (Winans et al., 2017). After considering 114 conceptual frameworks, Kirchherr and colleagues (Kirchherr et al., 2017) define it as an economic system that substitutes product end-of-life with a set of circularity interventions.

Circularity interventions are actions or processes that preserve resources inside the economy (Bocken et al., 2017; Lieder & Rashid, 2016). Such actions are based on three principles (EMF, 2013; Ghisellini et al., 2016):

- Minimizing waste disposal through the use of waste flows as inputs for other economic activities;
- Optimizing material loops through the design of products and services that allows extending product lifetime, reuse and recycling materials at their end-of-life;
- Promoting a restorative environment through the development of renewable energy that decreases material extraction and its environmental impacts.

Implementing circularity interventions has become a prominent topic in sustainability policies (McDowall et al., 2017). For instance, the European Commission presented an action plan for the circular economy in which interventions are related to the design of long-lasting products, material closed-loops at multiple supply chain levels, resource efficiency and sustainable waste management (EC, 2015). Another example is that of the Chinese circular economy initiatives of the 1990s, which seek to prolong product lifetime and to enhance resource efficiency (Geng et al., 2012, 2016). These and other governments have implemented circularity actions as mechanisms to achieve economic prosperity and environmental sustainability (Andersen, 2007; Geissdoerfer et al., 2017; Ghisellini et al., 2016).

In order to maximize the economic and environmental benefits of circularity interventions, it is important to assess their cost-effectiveness. This can be done through the application of analytical methods that assess the impact of particular policies (Elia et al., 2017; Potting et al., 2017). However, there is no recognized framework for measuring how effective a country is in making a transition to circularity (EEA, 2016; Linder et al., 2017). Such an approach needs to integrate indicators with a clear understanding of the circularity mechanism influencing multiple economic activities and their environmental performance (Lieder & Rashid, 2016; Pauliuk, 2018).

The assessment of circularity interventions can be addressed by environmentally extended input-output analysis (EEIOA). In fact, as described further below, EEIOA has been used to evaluate the impacts of residual waste management, reusing and recycling activities, product lifetime extension, and resource efficiency (Duchin 1992; Iacovidou et al., 2017).

Assessing these interventions through EEIOA has in turn required adapting that same framework, leading to the development of new methods. For example, the study of the interdependency between production and waste generation led to the development of waste input-output models (S. Nakamura, 1999). In addition, the analysis of resource use and emissions at country level in relation to potential leakage on a global level (Böhringer &

Rutherford, 2015; WEF, 2014) resulted in the development of multiregional models for assessing the impacts embodied in international trade (Peters & Hertwich, 2009; Tukker & Dietzenbacher, 2013; Wiedmann, 2009). Finally, circularity interventions are usually implemented using financial incentives such as subsidies and taxes, that need to be endogenized to account for all impacts of the policy (Ferrão et al., 2014). The theoretical integration of financial incentives in the waste input-output model was achieved by Rodrigues et al. (2016). Such adaptations of EEIOA framework have been relevant to evaluate the potential impacts of current circular implementation.

To promote the further advancement and implementation of best practices in the use of EEIOA to assess the economic and environmental implications of circularity interventions, it is important to critically evaluate existing studies. To the best of our knowledge no such review has previously been compiled.

We fill this knowledge gap by offering a literature review of EEIOA-based circularity interventions and suggest opportunities for improvement. Chapter 2 proceeds as follows. Section 2.2 describes the data and methods used in the literature survey. Section 2.3 presents the actual literature review, describing how in the past circularity interventions have been addressed, organized around four categories: residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Section 2.4 synthesizes the main methodological aspects of each intervention type. Section 2.5 then discusses the major contributions and limitations as well as opportunities for improvement and Section 2.6 closes with some final remarks.

2.2. Method and data

In order to facilitate the identification of EEIOA-based studies related to circular strategies, we organized circularity interventions based on the resource flow framework proposed by Ellen MacArthur Foundation (2013), Bocken et al. (2016), and Kirchherr et al. (Kirchherr et al., 2017). Given such framework, we then collected 13 keywords that are commonly used to identify circular strategies (Bocken et al., 2017; den Hollander et al., 2017a; Ghisellini et al., 2016). Table 2.1. shows the categories evaluated in this review as well as their definition and corresponding keywords.

Table 2.1. Circularity intervention categories

Intervention category	Description	Based on	Keywords
Residual waste management (RWM)	Related to post-consumption activities where the materials are disposed outside the economy	Ellen MacArthur Foundation (2013) Kirchherr et al. (Kirchherr et al., 2017)	landfill energy recovery waste treatment
Closing supply chains (CSC)	The re-integration of materials at different levels of the supply chain after being used, via for instance product reuse, component re-use, refurbishing, and recycling	Bocken et al. (2016) Ellen MacArthur Foundation (2013) Kirchherr et al. (Kirchherr et al., 2017)	reuse redistribution refurbishment remanufacture recycle
Product lifetime extension (PLE)	Associated with slowing-down the resource use as a consequence of extending lifetime of products, via for instance design for longevity and improved maintenance	Bocken et al. (2016) Kirchherr et al. (Kirchherr et al., 2017)	product lifetime extension maintenance repair

Resource efficiency (RE)	Processes or mechanisms which optimize resource flows by using less resources per unit produced	Bocken et al. (2016) Kirchherr et al. (Kirchherr et al., 2017)	resource efficiency material efficiency

We applied the keywords of Table 2.1 to query online databases of peer-reviewed scientific publications in English (i.e. Web of Science and Scopus) and identified 163 documents that combined “Input-Output Analysis” and at least one term related to circularity interventions when screening title, abstract and keywords. Afterwards we manually examined the content of the documents, restricting our analysis to 47 relevant documents. We then developed a backwards/forwards snowballing process (Wohlin, 2014), identifying additional relevant literature from the citation network. In total we found 93 relevant documents.

In order to identify basic attributes of the selected publications, we collected data on the year of publication and number of citations, circularity intervention covered, and EEIOA model characteristics.

Figure 2.1 shows the number of articles published in each year and the number of yearly citations of all previously published papers. The figure shows that there has been a gradual increase in the number of EEIOA-based studies that assess circularity, with 60% of all relevant literature published in the past five years. Figure 2.2 shows that the majority of studies are focused on the interaction between recycling and waste treatment systems (n[CSC+RWM] = 35). Moreover, residual waste management is the most common intervention, present in 68 study cases, followed by closing supply chains (n[CSC] = 54), product lifetime extension (n[PLE] = 17) and resource efficiency (n[RE] = 13).

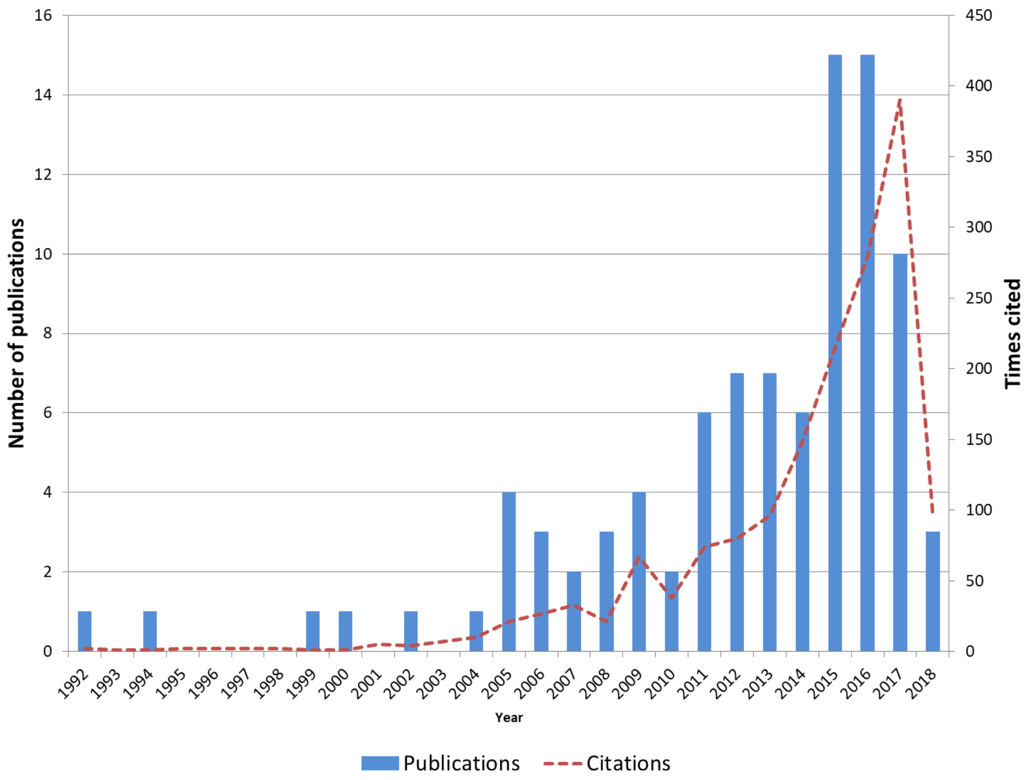

Figure 2.1. Number of publications and citations per year (status on 11 June 2018).

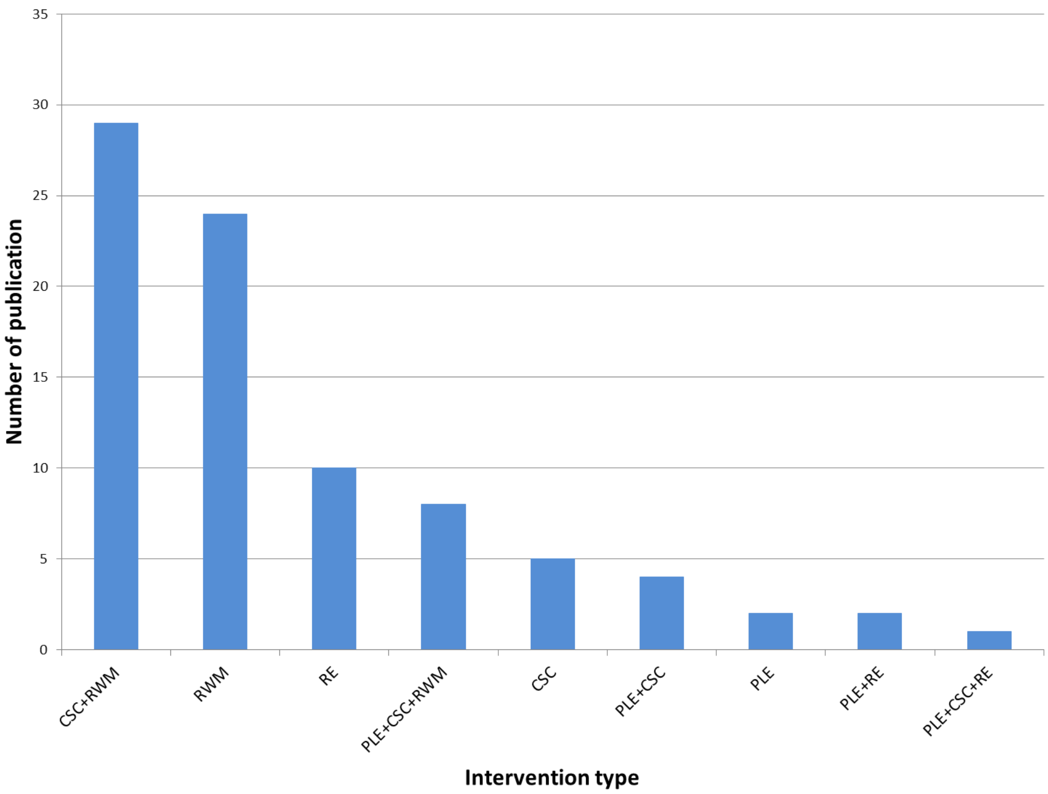

Figure 2.2. Number of publications per circularity intervention category (status on 11 June 2018). RWM = residual waste management; CSC = closing supply chains; PLE = product lifetime extension; and RE = resource efficiency

Table 2.2 presents a characterization of the top-10 most-cited papers. Table 2.3 provides a technical characterization of the type of model and/or approach used in different studies concerning the type of table, units, time and geographical scope. Most studies (88%) use harmonised input-output tables (IOTs), use hybrid units (53%), are focused on a specific year (85%) and are applied to a single country (75%). A detailed list of specific characteristics of the reviewed publication is provided in the supplementary material section.

Table 2.2. Overview of top-10 most cited articles related to the assessment of circularity interventions (status on 11 June 2018)

Reference	Intervention	Region	Sector	IO approach	Outcome	Citations
Wiedmann et al. (2015)	RE	Global	Multi-sectoral	MR EEIOA	Identification of material footprint hotspots at global scale	218
Nakamura & Kondo (2002)	CSC RWM	Japan	Waste management	WIOA	Evaluation of envrionmental impacts of waste treatment policies	146
Ferrer & Ayres (2000)	PLE CSC	France	Remanufactu ring	IOA	Evaluation of economic impacts of remanufacturing sector	78
Nakamura et al. (2007)	CSC RWM	Japan	Metals	WIO-MFA	Development of framework for identify material	72

					paths along the supply chain	
Duchin (1992)	RWM	United States	Waste management	IOA	Quantification of waste disposal and income changes for different scenarios	66
Takase, Kondo & Washizu (2005)	RWM	Japan	Households	WIOA	Impacts of household consumption on CO_2 and landfill use	65
Aye et al. (2012)	PLE CSC	Australia	Buildings	Hybrid IO-LCA	Impacts of prefabricated reusable building modules on GHG emission and energy	56
Nakamura & Kondo (2006)	CSC RWM	Japan	Electrical home appliances	Hybrid IO-LCA & IO-LCC	Environmental cost of end-of-life scenarios (landfill, recycling, design for disassembly, and lifetime extension)	39
Kondo & Nakamura (2004)	PLE CSC RWM	Japan	Electrical home appliances	Hybrid IO-LCA	Environmental impacts of end-of-life scenarios (landfill, recycling, design for disassembly, and lifetime extension)	37
Nakamura (1999a)	CSC RWM	Netherlands	Waste management & recycling	WIOA	Effects of recycling, efficiency collection and efficiency technology recycling	36

Table 2.3. Summary of EEIOA model characteristic by type of table, units, time and geographical dimensions

Model characteristic		Number of publications
Table	IOTs	82
	SUTs	11
Units	Monetary	39
	Physical	5
	Hybrid	49
Time dimension	Single year	79
	Time series	14
Geographical dimension	Single region	70
	Multi region	23

Although there are examples of circular intervention assessments at the macro-economic level developed by governments and private institutions in the grey literature (for example, Bastein et al., 2013; Böhringer & Rutherford, 2015; McKinsey&Company, 2016; Pratt & Lenaghan, 2015), most of these studies apply bottom-up methods, computable general equilibrium (CGE) models or other approaches rather than EEIOA (Winning et al., 2017). Apart from the fact that we wanted to focus primarily on the peer-reviewed literature, this was an additional reason to exclude this type of studies to focus in the identification of novel methods and best practices in EEIOA-based cases. Moreover, Chapter 5 will show the application of CGE and other macroeconomic models on assessing the impacts of circularity interventions

2.3. Results and discussion

We now perform a methodological review of EEIOA-based studies which assess residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Each intervention differs in its approach to splitting and extending sectors in the input-output tables, adjusting technical and final demand coefficients, and incorporating hybrid-unit data.

2.3.1. Residual waste management

Nakamura and Kondo (2009; 2002) introduced the harmonized waste input-output tables, which are used to determine the embodied waste of a certain consumption. The waste input-output analysis (WIOA) consists in a hybrid model constituted by economic and physical units in which are represented explicitly the interaction between industries and waste treatment sectors. This model allows to expand EEIOA in relation to the interdependence between goods and waste disposal.

Several studies applied the WIOA model to measure the direct and indirect waste of consumption at national level, such as Taiwan, France, and United Kingdom (Beylot, Vaxelaire, et al., 2016; Jensen et al., 2013; Liao et al., 2015; Salemdeeb et al., 2016). In a study at sub-national scale, Tsukui et al. (2011, 2017) developed an interregional WIOA to quantify the embodied waste generated by consumption patterns in the city of Tokyo. These cases applied a traditional Leontief inverse matrix to estimate the embodied goods and waste of final demand.

By applying monetary supply-use principles in the WIOA framework, Lenzen and Reynolds (2014) developed a method to construct waste supply-use tables. They considered that a supply-use approach has an advantage because it includes the allocation matrix from WIOA model into the accounting system, which enables the simultaneous generation of industry and commodities multipliers (Lenzen & Rueda-Cantuche, 2012). In addition, a supply-use model can distinguish between multiple waste types and treatment methods. The researchers demonstrated that WIOA and WSUA multipliers were equivalents by employing Miyazawa’s partitioned inverse method. An application of WSUA was presented by Reynolds et al. (2014), in which the authors assessed the direct and indirect flows of waste generated by intermediate sectors of the Australian economy.

Fry et al. (2016) constructed multiregional waste supply-use tables by using Industrial Ecology Virtual Laboratory as a computational platform (Lenzen et al., 2014). They measured the waste footprint of Australian consumption considering the impacts of imports. The authors also focused on the impacts driven by consumption pattern in each Australian state and territory, which showed the waste footprint at sub-national level.

Similarly, Tisserant et al. (2017) developed a harmonized multiregional solid waste account using coefficients from physical and monetary values from EXIOBASE v2.2.0 (Tukker et al., 2013; Wood et al., 2015). They collected the data from 35 waste treatment services (measured in tonnes) that were used to calculate global waste footprint and identify the main sectors contributors per country. With the outcome of waste footprint, they evaluated the possibility of achieving targets for material recycling proposed by European Commission in the Circular Economy Package (EC, 2017).

By extending satellites accounts, Lin et al. (2013) introduced a wastewater material composition vector that distinguishes the composition of wastewater flows. In addition, Court et al. (2015) incorporated an accounting system for hazards waste materials as an extension of EEIOA.

In a study of landfilling scenarios using waste input-output tables, Yokoyama et al. (2006) created additional sectors of ‘landfill mining’ and ‘gasification’. These activities were evaluated in scenarios of increasing gasification industry demand and adopting new landfill infrastructure. The scenarios required the adaptation of technical coefficients, which imply positive and negative values depending on the interaction between industries. For the final demand, the authors assumed that consumption pattern is proportional to domestic population growth and, then, they fixed the respective final demand values. Their final outcome showed the impacts on CO_2 emissions and waste generation under certain assumptions of sustainable waste management.

Duchin (1990, 1992) proposed an analysis of waste treatment scenarios by adapting technology matrix and final demand values in EEIOA framework. In her studies, the author computed numerical examples and identified waste disposal in final consumption by adjusting final demand values in a static model. This approach described an entire economy in terms of its sectors and their interrelationships, which account for the environmental impacts.

By converting the monetary values of input-output tables into physical units, Nakamura et al. (2007) proposed a material flow analysis (MFA) that uses monetary coefficients to express inter-industrial physical flows. The waste input-output material flow analysis (WIO-MFA) was used to trace the final destination of materials and their specific elements through the supply chain (Nakajima et al., 2013; S Nakamura et al., 2009; S Nakamura & Nakajima, 2005; Ohno et al., 2014). For example, in an analysis of metal industry, Ohno et al. (2016) applied the WIO-MFA to assess the material network of metals and alloying elements. For creating the network, they developed three steps: to disaggregate sectors and convert monetary to physical units; to calculate the technical coefficients; and to multiply the input coefficient matrix with two filtering matrices, which are physical flow filter as a binary matrix for excluding non-physical flows and the loss filter matrix that removes inputs that are related to process waste.

From a product-level perspective, Nakamura and Kondo (2006) evaluated the end-of-life scenarios of electric home appliances, landfilling, shredding, recycling, and recycling with design for disassembly, by combining the WIOA framework and life cycle costing analysis. Reynolds et al. (2016) also demonstrated the use of waste input-output life cycle assessment (WIO-LCA) in the context of New Zealand food waste. They included mass values, economic cost, calories and resources wasted accounts as model inputs. In a recent study, Reutter et al. (2017) combined input-output multipliers with the Australian economic cost of food waste, which can be used to quantify the embodied net surplus of wasted food.

2.3.2. Closing supply chains

To assess 3R's economic activities (recycling, reuse and reduction), Huang et al. (1994) collected data to include these sectors in a supply-use framework. They applied a traditional Leontief approach in which each new industry produces a single economic commodity. By using such assumption, the authors allocated the monetary flows of recycling and reuse sectors in a new supply-use table that allows to analyze policy initiatives related to closing supply chains.

Nakamura (1999) applied a similar principle to create a harmonized industry-by-industry framework that accounts for recycling activities. He represented the flow of goods and services, waste, and pollutants among five industries that include recycling sectors. Such activities were expressed by both physical and monetary units because, in many cases, the market value of waste was not represented in accounting system.

In an analysis of electronics waste recycling, Choi et al. (2011) constructed an EEIOA model that collects data for recyclable end-of-life products and related economic sectors. They considered e-waste values in a satellite account that is connected to recycling sectors in a similar way as primary materials are linked to mining industries. The authors then included a new industry and product categories for recycling activities as well as the adjustment of environmental extension to represent the e-waste flows through the supply chain.

For assessing the economic impact of product recovery and remanufacturing in France, Ferrer and Ayres (2000) incorporated the remanufacturing sector in a harmonized industry-by-industry matrix. This harmonized system was adjusted to consider different demands in labor, energy, primary materials, and inputs from others economic sectors. They assumed that the manufacturing and remanufacturing final demand in physical values were equivalent, however, remanufacturing products have a lower price value. They quantified the impacts of the new sector in terms of market share and labor increase.

Beylot et al. (2016) studied the potential contribution of waste management policies to reduce carbon emissions and resources use. The authors used WIOA obtaining physical units from the French physical supply-use tables. These physical values were used to calculate technological requirement matrices related to waste flows. By considering changes in final demand coefficients, they established scenarios to increase recycling rates and to adopt available best technologies for waste incineration. The scenarios of closing supply chains were extrapolated to evaluate the short-term impacts of recycling policies.

Focusing on the case of Australian consumption, Reynolds et al. (2015) evaluated the effects of non-profit organizations on reducing food waste. In a waste supply-use table, they created a new ‘food charity’ sector, and extrapolated food waste data from government and industry reports by using a top-down estimation method. According to Reynolds et al. (2016), this technique allows to estimate waste flow per industry simultaneously but separately in which each waste flow has a unique composition that is defined by the direct production inputs. Such a relationship is provided by the technology matrix, which is also connected to available waste data to construct the new intermediate sector.

In a study investigating the impact of Portuguese packaging waste management, Ferrão et al. (2014) analyzed the effects of municipal waste and recycling strategies on economic added value and job creation. They described four basic types of recycling materials: paper and wood, plastic, glass and metals. For each material type, they considered that the magnitude of recycling sector relative to the respective non-recycling activity is brought by the ratio of the net payback value to the total amount of intra-sectoral transactions. The researchers adjusted the ratio of recycling and non-recycling materials in order to evaluate waste management scenarios for packaging alternatives.

In an analysis of tire industry, Rodrigues et al. (2016) modified a waste supply-use model to recognize the effects of policies related to closing supply chains, such as extended producers responsibility. In this scheme, waste management is financed by compensation that is represented as producers’ fees in terms of waste volume processed. The researchers modeled the flow of compensation fees by introducing the financial requirements of waste management under the adapted waste supply-use table. They also adjusted the coefficients of waste treatment intermediate industries in the technical matrix and introduced an exogenous stimulus that is used to compare a reference scenario and the alternative strategy.

To explore the optimal structure of end-of-life treatment and recycling strategies, Kondo and Nakamura (2005) introduced a model that integrates WIOA into a linear programming analysis (WIO-LP). The researchers replaced the fixed constant values of waste input-output tables with an adaptable allocation matrix that can respond to specific constrains. This approach is generally defined as a minimization problem. For example, Lin (2011) applied the WIO-LP model to analyze the optimal system configuration for reducing environmental loads, such as CO_2 emissions from wastewater treatment. The researcher considered a set of constraints to reduce the amount of a certain type of environmental impacts generated by both producing and waste treatment sectors.

In a recent study, Ohno et al. (2017) evaluated the optimal scenarios of steel recycling for end-of-life vehicles in Japan through the integration of linear programming into a waste input-output material flow analysis. They considered quality-oriented scrap recycling and identified which scenarios can contribute to obtain the maximal potential of recovery for alloying elements.

By using industrial accounts for the Taiwanese economy, Chen and Ma (2015) assessed the linkages of industrial material and waste flows at national level. They rearranged the structure of the accounting system to adopt a framework that resemble the WIOA. This accounting system enables us to identify eco-industrial network patterns, for example, by examining the potential of by-products as inputs for other industries.

2.3.3. Product lifetime extension

In an assessment of the Japanese automobile industry, Kawaga et al. (2008) studied the implications of changing passenger vehicle lifetime. They applied a cumulative product lifetime model that is used to describe the patterns of final consumption. This approach is used to adjust the final demand for the scenarios of extending automobile lifetime. The authors then developed a structural decomposition analysis (SDA) with the new scenarios in order to quantify the drivers of end-of-life automobile between certain periods.

Takase et al. (2005) extended the Japanese household final demand in the WIOA for assessing waste reduction scenarios based on sharing transport services and long-lasting products. These schemes were analyzed by adjusting final demand coefficients. In sharing transportation, for example, the authors explored a scenario in which users replace private cars for the use of train. This scenario was expressed by increasing goods in public transport services and decreasing car industry outputs. They changed the coefficient in each scenario and compared the embodied waste disposal and CO_2 emissions. In addition, they incorporated potential rebound effects, by assuming a fixed budget for final demand and allocating proportionally the remaining budget to all goods in the new consumption portfolio.

In a further study, Kagawa et al. (2015) adapted WIOA framework to the lifetime distribution model, which is used to forecast secondary material flows demand and supply. They incorporated a stationary stock variable in the lifetime distribution analysis and expressed stocks, discarded and newly purchased products in function of time. These variables were inserted in the final demand, which implies a dynamic function that can be used to predict future demand. In a similar way, secondary supply flows were predicted by the disposal of scraps materials at end-of-life.

Shortly after, Nishijima (2017) used an EEIOA integrated to lifetime distribution analysis for quantifying the effect of extending air conditioners lifetime on CO_2 emissions. He calculated the new final demand for household air conditioners by multiplying the production price per air conditioner unit and the number of new air conditioners sold. By adjusting final demand, he performed a structural decomposition analysis to assess the effects of changes final demand, technical and direct CO_2 emissions confidents in air conditioners sectors.

Duchin and Levine (2010) introduced an EEIOA framework for estimating the average number of times that a resource passes through each supply chain stage. They established the principles of transforming input-output tables to an Absorbing Markov Chain (AMC) model based on their mathematical characteristics. For instance, both approaches are matrix-based and can represent transaction flows through different economic activities. The monetary flows from the input-output framework are analogous to the AMC's transition states, which represent the probability of a resource to move throughout sectors.

A key study evaluating AMC attributes is that of Eckelman et al. (2012), in which they argued that the AMC approach lays the first stone from the resource extraction as downstream perspective, instead of the upstream consumption-based approach that it is considered in a traditional EEIOA framework.

In a follow-up research, Duchin and Levine (2013) integrated the AMC into a linear programming model that distinguishes key sections of resource-specific network. This integrated model brought detailed insights about the structure of global resource interaction. Furthermore, the model constrained multiregional factors that were adapted to minimize global resource use to satisfy specified final demand.

In a study investigating the distribution of metals over time along the supply chain, Nakamura et al. (2014) established a IO-based dynamic MFA model that considers open-loop recycling and explicitly takes into account scrap quality and losses at production stage. This approach was constructed by converting the monetary coefficients of input-output tables into physical representation for the MFA model. Their work on MaTrace model was complemented by Takeyama et al. (2016) study of alloying steel elements in Japan. They applied MaTrace framework to demonstrate the potential reduction of alloying elements dissipation.

More recently, Pauliuk et al. (2017) developed the dynamic approach in a multiregional context, which was used to determine regional distribution and losses of steel production throughout multiple lifetime stages. They described their 'MaTrace' model as a supply-driven approach that traces down specific materials in life cycles of multiples products and complement the life cycle perspective, which is compared with other techniques, such as AMC and Ghosh inverse matrix. The researches also introduced a material-based circularity indicator by considering the cumulative mass of material present in the system over a certain time interval in terms of an ideal reference case.

2.3.4. Resource efficiency

In an analysis of material use for Japanese household consumption, Shigetomi et al. (2015) decomposed the household final demand into the consumption expenditures by householder age bracket. The disaggregated expenditures were used to quantify the material intensity of each household group, which represented the material hotspots of final demand. The authors identified the major contributors to the material footprint and projected future consumption trend based on a linear regression model. This analysis assumed that future household size will be proportional to the predicted population growth.

Skelton et al. (2013) explored the impacts of material efficiency on key steel-using industries by the application of multi-regional input-output (MRIO) approach. They focused on an upstream perspective to seek opportunities through the supply chain of steel. A diagonal final demand vector was applied to identify the final destination of steel output from each sector. They assessed the major contributors to the footprint in terms of their potential incentives to implement material efficiency strategies. They measured such incentives in a supply-side approach based on the Ghosh inverse matrix (Miller & Blair, 2009). This method allows to quantify the effects of changing the value added. The researchers performed price changes assuming that carbon tax scenarios are implemented. The fixed prices were applied to the system in order to measure the variation in the share of input expenditure that goes on the steel sector, which expresses the incentives of each industry for incorporating material efficiency practices.

Giljum et al. (2015) analysed geographical trade patterns identifying the embedded materials on a bilateral basis. They extended the MRIO model by adding material extraction data. This dataset was grouped into four broad types: metals, minerals, fossil fuels and biomass. Each classification was used to calculate the domestic material consumption and raw material consumption per country. In the same way, Wiedmann et al. (2015) calculated material footprint time series that were used to represent the changes of resource productivity at global level. They presented a multivariate regression analysis for countries to understand the driving forces of national material footprints. A broader perspective has been adopted by Tukker et al. (2016) who estimated resource footprint considering the indicator dashboard of resource efficiency, which includes carbon, water, energy and land metrics (EC, 2011). The authors correlated each resource footprint to quality life indicators, namely human development index and happy development index, bringing a social dimension to resource efficiency measures.

2.4. Synthesis of EEIOA frameworks on the assessment of circularity interventions

In the following section, we synthesize the findings from the literature review in terms of the current application of EEIOA in a circular economy context. To illustrate the further development and best practices of such methods, we consider a simplified waste supply-use analysis (WSUA) based on Rodrigues et al. (2016). Although we found the application of traditional EEIOA and other hybrid models, we use the waste input-output approach because it shows a suitable framework for creating end-of-life scenarios, which are usually linked to the basis of circular strategies (Kirchherr et al., 2017).

Most of the studies suggested that WIOA can be applied to measure effectively the resource flows of circularity interventions. In addition, WIOA can benefit from a supply-use approach which can express the interaction of products and industries in a higher level of detail (Lenzen & Reynolds, 2014).

Figure 2.3 shows a basic waste supply-use table that contains three main parts: final demand vector (y), technology matrix (A) and intensity vector (b′). The y-vector is subdivided into final consumption of products (y^P) and final waste generation (y^W). The A-matrix is comprised of a set of submatrices that account for the direct requirements of products or services (P), sectors or industries (S), waste (W), and waste treatment or recycling sectors (T). The b′-vector shows the element of direct impact coefficients that correspond to the production intensities of the S and T sectors (e^S and e^T respectively).We can assess the effects of incorporating circularity interventions by adjusting final demand and technology coefficients. Several authors applied changes in y-vector and A-matrix to explore the scenarios of enhancing waste treatment and recycling activities (Beylot et al., 2018; Beylot, Boitier, et al., 2016; for example, Yokoyama et al., 2006). In many cases, representing these sectors would require the extension of intermediate demand to account explicitly for the specific flows of each circular strategy.

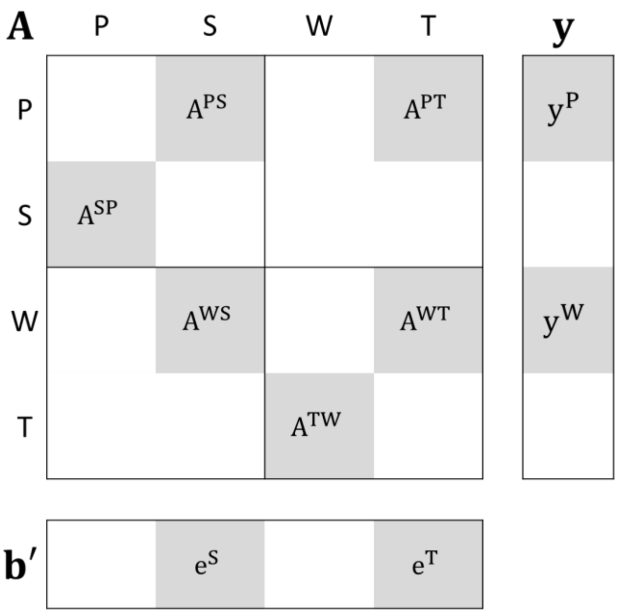

Figure 2.3. Simplified waste supply-use table. y = final demand vector; A = technology matrix; b'= intensity vector. P = product or service, S = sector or industry, W= waste, T = waste treatment or recycling activity. y^P elements are monetary values (M.EURO). y^W elements are physical units (tonnes). A^{PS} and A^{SP} elements are coefficients from monetary units (M.EUR/M.EUR). A^{WS} elements are coefficients from physical and monetary units (tonnes/M.EUR). A^{TW} and A^{WT} elements are coefficients from physical units (tonnes/tonnes). A^{PT} elements are coefficients from monetary and physical units (M.EUR/tonnes). e^S elements represent coefficients from physical values, depending on the environmental pressure, and monetary units (e.g. CO_2 tonnes /M.EUR). e^T elements represent coefficients from physical

values, depending on the environmental pressure, and physical units (e.g. CO_2 tonnes/tonnes). Empty cells contain zeros.

Considering a reference scenario $(\mathrm{y}, \mathrm{A}, \mathrm{b}')$, it is possible to adapt the intermediate flows and final demand coefficients to represent the changes of new circularity actions $(\mathrm{y}^{\mathrm{alt}}, \mathrm{A}^{\mathrm{alt}}, \mathrm{b}'^{\mathrm{alt}})$. We then can calculate the embodied impacts of the reference scenario (m) and the alternative circular strategy $(\mathrm{m}^{\mathrm{alt}})$ by a traditional Leontief inverse (Miller & Blair, 2009), as is shown in equations [2.1] and [2.2]:

$$\mathrm{m} = \mathrm{b}'(\mathrm{I} - \mathrm{A})^{-1}\mathrm{y}; \quad [2.1]$$

$$\mathrm{m}^{\mathrm{alt}} = \mathrm{b}'^{\mathrm{alt}}(\mathrm{I} - \mathrm{A}^{\mathrm{alt}})^{-1}\mathrm{y}^{\mathrm{alt}}. \quad [2.2]$$

The net effect of circularity interventions $(\Delta\mathrm{m})$ can be quantified by the difference of m and $\mathrm{m}^{\mathrm{alt}}$ (see equation [1.3]). This net impact could represent a measure for the potential effect of a specific circularity scenario. For example, if we analysed the implications of a certain circularity action on carbon footprint and the net effect would be a positive value (i.e. $\Delta\mathrm{m} > 0$), it means that the alternative circularity scenario has less impact than the reference stage on the embodied carbon emissions. Such avoided impact from the application of a circularity intervention could be used as point of comparison between different scenarios.

$$\Delta\mathrm{m} = (\mathrm{m} - \mathrm{m}^{\mathrm{alt}}). \quad [2.3]$$

We can synthetize the lessons from the literature to determine which are the best practices for constructing an alternative final demand $(\mathrm{y}^{\mathrm{alt}})$, technology matrix $(\mathrm{A}^{\mathrm{alt}})$, and intensity $(\mathrm{b}'^{\mathrm{alt}})$ that determine the effects of each circularity intervention. Based on the literature review, we then deduce the causality sequence of adapting scenarios for residual waste management, closing supply chains, product lifetime extension, and resource efficiency. The following sub-sections can be used as a reference point for analysing specific scenarios of circularity transition.

We now focus on the description of primary and secondary sequences for each circularity action. Primary sequence refers to the first element of an EEIOA that can be adapted in order to represent the implementation of a circularity intervention. Following a causality chain, the secondary sequence denotes the first order of indirect impacts in response to the primary stimulus. We schematise such sequences in order to demonstrate the adjustment of waste supply-use tables for modelling each circularity alternative. Figure 2.4 indicates casual links as follows: primary sequence (green square, solid line border '—'), secondary sequence (red square, dashed line border '---'), the up arrow ('↑') represents a relative increment of the technical coefficients on A-matrix, the down arrow ('↓') indicates a relative reduction of the technical coefficients on A-matrix, and the up-down arrows ('↑↓') represents sequences in which technical coefficients can be increasing or decreasing in different sectors or industries due to the same causal link. As in Nakamura and Kondo's approach (2002), the A-matrix might contain negative values that show the causality sequence of waste flows thought economic activities. For instance, the inputs of recycling activities can be expressed as negative inputs of treatment sectors that would be required if recycling processes were not available (Shinichiro Nakamura & Kondo, 2002).

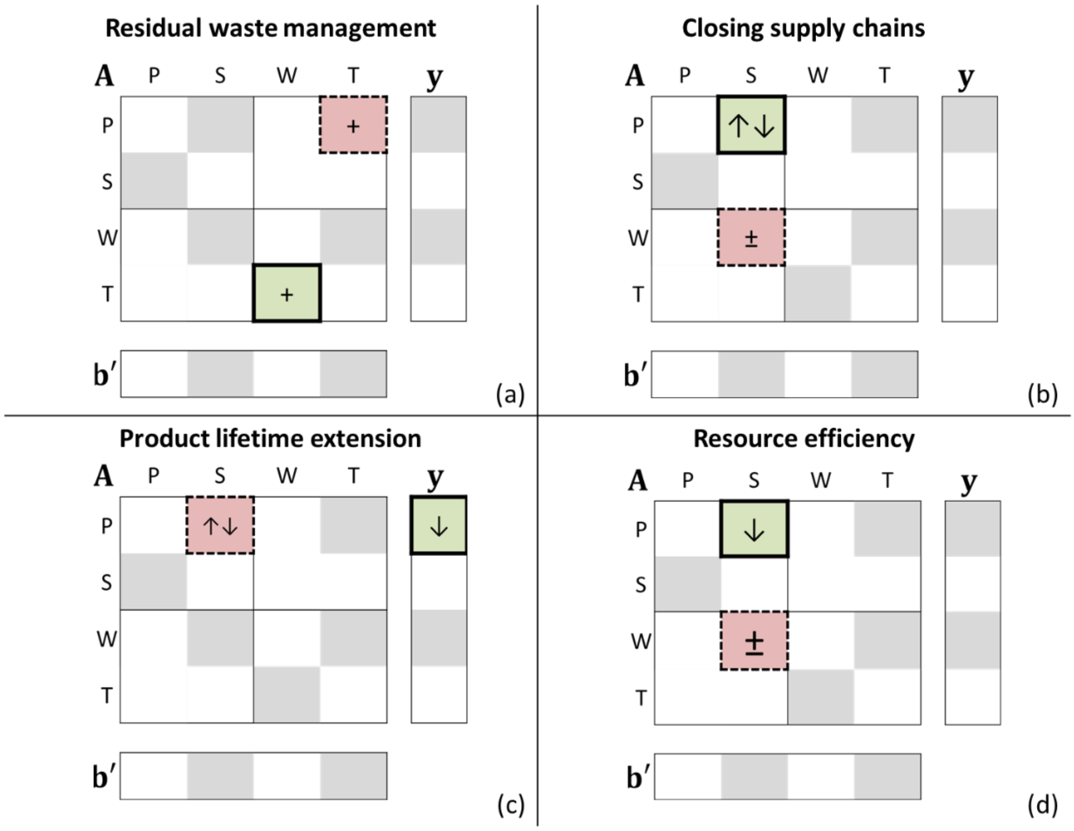

Figure 2.4. Modelling causality sequence of (a) residual waste management, (b) closing supply chains, (c) product lifetime extension, and (d) resource efficiency. y = final demand vector, A = technology matrix, b'= intensity vector. P = product or service, S = sector or industry, W= waste, T = waste treatment or recycling activity. Green square with solid line border ('—') indicates primary sequence, and red square with dash line border ('---') represents secondary sequence. '↑' indicates a relative increase of A-matrix coefficients, '↓' indicates a relative decrease of A-matrix coefficients, '↑↓' indicates a simultaneous change in different sectors or industries caused by the same causal link.

2.4.1. Modelling residual waste management

Residual waste management can be modelled by adjusting the amounts of waste treated by specific waste treatment sectors. Several authors created new waste treatment with improved technology (Beylot, Vaxelaire, et al., 2016; Liao et al., 2015; for example, S Nakamura & Kondo, 2009), which could be added to a waste supply-use table. These activities would require to augment their inputs from the rest of the economy in order to process the quantity of waste established in a specific circularity scenario (Yokoyama et al., 2006).

Figure 2.4(a) shows the causality sequence of changing the A-matrix for reducing waste scenarios. As primary sequence, wasted materials require to be absorbed by waste treatment sectors (↑ in A^{TW} elements). A secondary effect of such action is an increase on the direct requirements of waste treatment sectors in order to satisfy the new intermediate demand (↑ in A^{PT} coefficients). As a consequence of rising production, waste disposal from waste treatment activities and their suppliers are expected to increase (↑ in A^{WT} and A^{WS} elements). This sequence appears to create an ongoing loop where absorbing waste would lead to increase waste disposal in order to process the new residuals. However, disposal would need to be constrained by the processing capacity of waste treatment sectors. In our present framework, we do not focus on how capacity constraints should be modelled explicitly, nevertheless, we consider it to be an important aspect for future studies.

It is important to notice that, in some cases, the causality sequence could not be represented by changes in the A-matrix block. For example, increasing A^{TW} coefficients might not lead to an increment of A^{PT} coefficients directly. Instead, a secondary sequence can be observed in changes on the intermediate demand block of waste treatment inputs.

2.4.2. Modelling closing supply chains

Closing supply chains can be modelled by changing input and output coefficients to closed-loop activities, such as reuse and recycling sectors. These sectors can be represented as new end-of-life systems that would use waste outputs from industries as inputs to generate a usable product for the economy (Chen & Ma, 2015; S Nakamura & Kondo, 2006). In many cases, such new activities would be added to EEIOA in order to model specific material recycling (Choi et al., 2011; for example, Ferrer & Ayres, 2000; C. J. Reynolds et al., 2015).

A common assumption is that closing supply chains would drive the reduction of extracting virgin materials as a consequence of their replacement with secondary circular flows (Ferrer & Ayres, 2000). This substitutional approach can be modelled by the replacement of specific commodities in the use matrix of industries by secondary materials, components, etc. (i.e. ↑↓ in A^{PS} coefficients).

Figure 2.4(b) presents the causality sequence of closing supply chain scenarios. The primary sequence of closed-loop strategies would imply to adapt the use matrix of a specific industry. Assuming that industry (S) would replace a primary product (P') for a secondary material from a recycling activity (P''), then, the coefficients of the A^{PS}-matrix would decrease for the virgin materials (↓ for $a^{P'S}$). Likewise, the direct requirements of S would rise for the input of secondary goods (↑ for $a^{P''S}$). A proportional exchange between P' and P'' can be expressed by monetary terms, if the prices of both products are fixed, as well as by direct substitution in physical units (Ferrão et al., 2014; Ferrer & Ayres, 2000). Following the secondary sequence, we observe the adjustment of waste fractions treated by waste treatment industries (↑↓ in A^{TW} elements). Such an effect is considered because the replacement of P' for P'' could adapt as well the waste generated by industry S, and, then, changing direct requirements from waste treatment sectors in order to dispose the new fractions of waste.

2.4.3. Modelling product lifetime extension

The scenarios of extending product lifetime can be modelled by combining an adjusted final demand and the input coefficients in production sectors, next to probably a higher input of maintenance activities. In general, it is expected that the extension of product lifetime would decrease the quantity of goods consumed by final demand (Kagawa et al., 2009; Nishijima, 2017). Therefore, a primary effect of prolonging product lifetime would involve a reduction of final consumption on a certain product (y_i^P).

Figure 2.4(c) illustrates the causality chain of product lifetime extension. Assuming that a product i is designed to maximise its durability, the demand of such good would expect to decrease (↓ for y_i^P). Although this effect might imply an improvement of environmental performance from reducing the consumption of product i, the potential economic savings could be expended in other goods or services thus obtaining a rebound (Zink & Geyer, 2017).

A possible approach to account for these rebound effects is proposed by Takase et al. (2005). They suggested that the total expenditure of new final demand (x^P) would remain the same as total consumption in the reference scenario (x). By applying their assumption, we can distribute a leftover budget proportionally to the rest of goods and then include a quick estimation for the rebound effect in the alternative final demand (y^{P^*}), as is shown in equation [2.4]:

$$y^{P^*} = y^P \left(\frac{x}{x^P}\right). \quad [2.4]$$

As a secondary effect, it is possible that extending product lifetime could potentially require the adjustment of the production recipe, which leads to change in the input requirements of industries (Bakker et al., 2014; den Hollander et al., 2017b). However, there are only limited opportunities for consumers to prolong their product's lifetime when the product design is unchanged.

Depending on the product design, some industries might require to increase their material inputs in order to manufacture a more durable product (Murray et al., 2015). This operational adjustment is expressed in figure 2.4(c) by the simultaneous increment and reduction of technology matrix coefficients (in A^{PS}). For example, if a change of the production recipe for obtaining a durable good would require to reduce the input of commodity i and to increase the input of product k, then, we can model such adjustments on the A^{PS}-matrix (by ↑ for $a^{PS}_{k,j}$ and ↓ for $a^{PS}_{i,j}$).

2.4.4. Modelling resource efficiency

In comparison with the previous interventions, resource efficiency is the least studied of circularity actions from an EEIOA perspective (see figure 2.2), and it can be one of the most interesting in terms of future development of EEIOA method. We found that studies related to resource efficiency are mostly focused on the calculation of resource footprint as an aggregated value (for example, Giljum et al., 2015; Tukker et al., 2016; Wiedmann et al., 2015). However, resource footprint by itself does not capture if resource efficiency policies would be beneficial for reducing the extraction material from the environment or if it would contribute to minimise waste disposal. For assessing the impacts of resource efficiency measures, we can consider the effects of such intervention by lowering input coefficients at the same output.

Figure 2.4(d) presents the casual links of resource efficiency actions. In terms of primary sequence, it is possible that the application of material efficiency can lead to reduce the input requirements of economic activities where such intervention is implemented (↓ in A^{PS} coefficients). In a similar sequence as in modelling closing supply chain (see section 2.4.2.), a secondary implication of changes in A^{PS} can be expected in the operational changes of waste treatment, in which the technical coefficients of waste treatment sectors can be adapted as a response of variations in waste disposal (↑↓ in A^{TW} elements). To compare different scenarios, it is important to consider an accounting system in which the A^{PS}-matrix is expressed in physical terms because the use of monetary units as proxy can misrepresent physical reality (Dietzenbacher, 2005).

2.5. Discussion

In this review, our purpose was to critically evaluate the current application of EEIOA on the assessment of circularity interventions. We now focus on the main contributions and limitations of EEIOA in order to bring a possible direction for the development of such method in the assessment of circular strategies.

From the reviewed studies, we found a common agreement on how the assessment of circularity can be benefit from the development of EEIOA in which end-of-life scenarios are integrated. Such models usually are comprised of hybrid-units in which secondary and waste flows can be considered (Lenzen & Reynolds, 2014; for example, S Nakamura & Kondo, 2009). In addition, identifying these flows at multiregional scale has led to a better understanding of the impacts of international trade on resource and waste footprints in specific countries (as in Faye Duchin & Levine, 2013; Fry et al., 2016; Tisserant et al., 2017; Tukker et al., 2016; T. O. Wiedmann et al., 2015).

On the other hand, we observed that a major aspect to develop is the representation of flows as economic transactions. The monetary values of input-output tables could not address effectively the allocation of resource flows because the monetary values per physical units can differ significantly in several supply chains (Weisz & Duchin, 2006). This variation is caused by the assumption of an average price for materials with diverse physical properties and qualities (Tukker et al., 2016).

Price variation could become a critical factor in EEIOA with high sectorial and product aggregation (Wiedmann et al., 2015). It is likely to be a limitation for adequately tracing specific resource flows. For instance, if we assessed the recycling and reuse flows of a specific material such as 'recovered aluminum', input-output tables with broad classification of materials and industries (e.g. 'metal products' and 'mining sector') would assume that the price per physical value of 'recovered aluminum' is equivalent to the value of aggregated 'metal products'. This example shows that a highly aggregated EEIOA could in many cases be too limited to model specific material flows.

To avoid the deficiency in resolution of some EEIOA models', a reasonable approach could be to disaggregate products and sectors in more detailed categories. The new classification may contribute to monitor specific resource flows in a circular economy model (as shown by Choi et al., 2011; Li et al., 2013). However, disaggregating sectors in EEIOA presents a challenge by itself because sectoral data may not be available at the required level of detail. This is particularly the case in waste input-output frameworks, in which many studies show a limited dataset to split and link waste treatment sectors to the rest of the economy (Salemdeeb et al., 2016).

According to the studies, a lack of data sets for waste and material recovery could represent an issue in terms of waste valuation. Several authors recognized a deficiency for accounting the economic value of waste as this could be lower or absent in the EEIOA model (Liao et al., 2015; S Nakamura, 1999). The lack of economic valuation renders input-output accounts incomplete and, in some cases, leads to the underestimation of the embodied waste generated by final demand. For example, in the study of the Australian waste footprint by Fry and colleagues (2016), waste flows related to overseas production could not be considered due to the lack of waste values in other regions. This led to an underestimation of waste footprint resulting from Australian consumption by at least 1.5 million tonnes.

Underestimating waste generation may be caused by three aspects (Tisserant et al., 2017). First, some waste treatment sectors might not be included in the EEIOA model. Second, a standard EEIOA does not consider informal or illegal activities that could affect the estimation of waste footprint. Finally, EEIOA might not capture some of the flows that are not linked to monetary or physical transactions between sectors (i.e. direct reuse flows). In general, these aspects have an impact on the quality of waste data availability in many countries, which can be a significant source of uncertainty.

To address the lack of specific-sectoral data, proxies that can be used to integrate the values of circular strategies into the EEIOA framework could be estimated. For instance, to identify the patterns of industrial waste disposal, Reynold and colleagues (2016) suggested that the shares of waste generation in New Zealand presented the same trend as others developed economies (e.g. UK and Australia) and, then, used a proxy for the estimation of waste generation. In many cases, this type of assumption introduces uncertainties that may affect the analysis reliability (Ohno et al., 2016). Although the importance of uncertainties is considered in the literature (Wiedmann 2009), most of the reviewed studies mention the level of uncertainty without addressing it in much detail, and it brings a recurrent issue about data reliability of analyzing circular economy interventions with EEIOA.

In terms of modelling circularity scenarios, EEIOA may be of limited use when assessing environmental implications in the future (de Koning, 2018). For example, by fixing technical coefficients of a circular economy scenario, EEIOA cannot capture the volume effects on prices as well as price effects on the use of certain products. Without additional model components (see, for example, Gibon et al., 2015), EEIOA has also limited opportunities to represent changes of energy systems in the future with environmental impacts that are different from the current way of production. Moreover, there is no direct feedback effect from nature to the economy in standard EEIOA, which restricts the assessment of different circularity gains.

2.6. Conclusion

This chapter presented a review of EEIOA-based studies that assessed the economic and environmental implications of residual waste management, closing supply chains, product lifetime extension, and resource efficiency interventions. We evaluated the selected articles based on their methodological characteristics in order to synthesize the main EEIOA-based frameworks used to analyze each circularity intervention. Furthermore, our results led to a point of reference for modelling future circular strategies at macro-scale by applying EEIOA.

By considering a simplified waste supply-use model, we explained the causality sequence of modelling circularity interventions. For residual waste management, a waste treatment action can be modelled by augmenting the values of waste absorbed by a certain waste treatment sector, which in turn requires more inputs from the rest of the economy in order to process the new amount of waste disposal.

Closing supply chains can be assessed by adjusting input and output coefficients for industries that adopt closed-loop strategies, which are related to the replacements of virgin materials with secondary circular flows. In addition, these interventions require to specify new sectors in the EEIOA model if the circular activities are not explicitly expressed.

Product lifetime extension can be modelled by adapting the final demand coefficients by expecting a reduction of final consumption. However, it is important to consider a potential rebound effect of prolonging product lifetime caused by the expenditures on other product or service categories from the savings on final demand. Furthermore, modelling product lifetime extension might involve accounting for potential changes of the production recipe of durable goods.

Resource efficiency intervention can be analyzed by reducing input coefficients while maintaining the output. Such action could minimize the input requirements of economic activities in which the intervention is applied, and it can be used to model the structural changes in a technology matrix caused by resource efficiency strategies.

We observe that the development of waste input-output analysis (WIOA) will dominate the assessment of circularity transition, because it is the most suitable framework to link the flows of waste and the rest of the economy in an EEIOA system. However, WIOA is constrained by the monetary flows in EEIOA (S Nakamura & Kondo, 2009), which can be considered a major limitation for the analysis of circular strategies, especially in the case of residual waste management, due to the lack of valuing waste. This challenge can be avoided by future applications of physical and hybrid tables that can be used to analyze the potential impacts of material efficiency and secondary flows more accurately (Tisserant et al., 2017).

The recent development of hybrid-unit input-output and supply-use tables, in which tangible products and waste types are expressed in physical units (i.e. mass) and service sectors in monetary units (for example, Merciai & Schmidt, 2018), will advance the modelling of circularity interventions in a consistent framework. In addition, detailed sectoral data could enable the assessment of circular strategies such as re-use, remanufacturing, and refurbishment (EMF, 2013). Combining both aspects, hybrid tables and detailed production data, would allow an improvement of current EEIOA models for assessing the economic and environmental implications of a circularity transition.

2.7. References

Andersen, M. S. (2007). An introductory note on the environmental economics of the circular economy. *Sustainability Science*, *2*(1), 133–140. https://doi.org/10.1007/s11625-006-0013-6

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, *47*, 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049

Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production*, *69*, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Bastein, T., Roelofs, E., Rietveld, E., & Hoogendoorn, A. (2013). Opportunities for a Circular Economy in the Netherlands. Technical Report. In *TNO*. https://doi.org/10.3390/en1030105

Beylot, A., Boitier, B., Lancesseur, N., & Villeneuve, J. (2016). A consumption approach to wastes from economic activities. *Waste Management*, *49*, 505–515. https://doi.org/10.1016/j.wasman.2016.01.023

Beylot, A., Boitier, B., Lancesseur, N., & Villeneuve, J. (2018). The Waste Footprint of French Households in 2020. *Journal of Industrial Ecology*, *22*(2), 356–368. https://doi.org/10.1111/jiec.12566

Beylot, A., Vaxelaire, S., & Villeneuve, J. (2016). Reducing Gaseous Emissions and Resource Consumption Embodied in French Final Demand: How Much Can Waste Policies Contribute? *Journal of Industrial Ecology*, *20*(4), 905–916. https://doi.org/10.1111/jiec.12318

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bocken, N. M. P., Ritala, P., & Huotari, P. (2017). The Circular Economy: Exploring the Introduction of the Concept Among S&P 500 Firms. *Journal of Industrial Ecology*, *00*(0), 1–4. https://doi.org/10.1111/jiec.12605

Böhringer, C., & Rutherford, T. F. (2015). *The Circular Economy – An Economic Impact Assessment Report to SUN-IZA*. *June*, 1–33. https://sunstiftungsfonds.files.wordpress.com/2015/06/report-circular-economy.pdf

Chen, P.-C., & Ma, H. (2015). Using an Industrial Waste Account to Facilitate National Level Industrial Symbioses by Uncovering the Waste Exchange Potential. *Journal of Industrial Ecology*, *19*(6), 950–962. https://doi.org/10.1111/jiec.12236

Choi, T., Jackson, R. W., Green Leigh, N., & Jensen, C. D. (2011). A Baseline Input—Output Model with Environmental Accounts (IOEA) Applied to E-Waste Recycling. *International Regional Science Review*, *34*(1), 3–33. https://doi.org/10.1177/0160017610385453

Court, C. D., Munday, M., Roberts, A., & Turner, K. (2015). Can hazardous waste supply chain “hotspots” be identified using an input-output framework? *European Journal of Operational Research*, *241*(1), 177–187. https://doi.org/10.1016/j.ejor.2014.08.011

de Koning, A. (2018). *Creating Global Scenarios of Environmental Impacts with Structural Economic Models* [Leiden University]. https://doi.org/ISBN: 978-94-90858-55-1

den Hollander, M. C., Bakker, C. A., & Hultink, E. J. (2017a). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. *Journal of Industrial Ecology*, *21*(3). https://doi.org/10.1111/jiec.12610

den Hollander, M. C., Bakker, C. A., & Hultink, E. J. (2017b). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. *Journal of Industrial Ecology*, *21*(3), 517–525. https://doi.org/10.1111/jiec.12610

Dietzenbacher, E. (2005). Waste treatment in physical input-output analysis. *Ecological Economics*, *55*(1), 11–23. https://doi.org/10.1016/j.ecolecon.2005.04.009

Duchin, F. (1990). The conversion of biological materials and wastes to useful products. *Structural Change and Economic Dynamics*, *1*(2), 243–261.

https://doi.org/10.1016/0954-349X(90)90004-R

Duchin, F. (1992). Industrial input-output analysis: Implications for industrial ecology. *Proc. Natl. Acad. Sci.*, *89*, 851–855. http://www.pnas.org/content/89/3/851.full.pdf

Duchin, F, & Levine, S. H. (2010). Embodied resource flows and product flows: Combining the absorbing markov chain with the input-output model. *Journal of Industrial Ecology*, *14*(4), 586–597. https://doi.org/10.1111/j.1530-9290.2010.00258.x

Duchin, Faye, & Levine, S. H. (2013). Embodied Resource Flows in a Global Economy: An Approach for Identifying the Critical Links. *Journal of Industrial Ecology*, *17*(1), 65–78. https://doi.org/10.1111/j.1530-9290.2012.00498.x

EC. (2011). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Roadmap to a Resource Efficient Europe*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571

EC. (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Closing the loop - An EU action plan for the Circular Economy*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0614

EC. (2017). *Circular economy package Four legislative proposals on waste*. http://www.europarl.europa.eu/EPRS/EPRS-Briefing-573936-Circular-economy-package-FINAL.pdf

Eckelman, M. J., Reck, B. K., & Graedel, T. E. (2012). Exploring the Global Journey of Nickel with Markov Chain Models. *Journal of Industrial Ecology*, *16*(3), 334–342. https://doi.org/10.1111/j.1530-9290.2011.00425.x

EEA. (2016). *Circular economy in Europe - Developing the knowledge base* (Issue 2). https://doi.org/10.2800/51444

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

EMF. (2013). *Toward the circular economy. Technical Report*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Ferrão, P., Ribeiro, P., Rodrigues, J., Marques, A., Preto, M., Amaral, M., Domingos, T., Lopes, A., & Costa, E. I. (2014). Environmental, economic and social costs and benefits of a packaging waste management system: A Portuguese case study. *Resources, Conservation and Recycling*, *85*, 67–78. https://doi.org/10.1016/j.resconrec.2013.10.020

Ferrer, G., & Ayres, R. U. (2000). The impact of remanufacturing in the economy. *Ecological Economics*, *32*(3), 413–429. https://doi.org/10.1016/S0921-8009(99)00110-X

Fry, J., Lenzen, M., Giurco, D., & Pauliuk, S. (2016). An Australian Multi-Regional Waste Supply-Use Framework. *Journal of Industrial Ecology*, *20*(6), 1295–1305. https://doi.org/10.1111/jiec.12376

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy - A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of Cleaner Production*, *23*, 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005

Geng, Y., Sarkis, J., & Ulgiati, S. (2016). Sustainability, wellbeing, and the circular economy in China and worldwide. *Science*, *March*(April), 76–79.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gibon, T., Wood, R., Arvesen, A., Bergesen, J. D., Suh, S., & Hertwich, E. G. (2015). A Methodology for Integrated , Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environ. Sci. Technol.*, *49*, 11218−11226. https://doi.org/10.1021/acs.est.5b01558

Giljum, S., Bruckner, M., & Martinez, A. (2015). Material footprint assessment in a global input-output framework. *Journal of Industrial Ecology*, *19*(5), 792–804. https://doi.org/10.1111/jiec.12214

Huang, G. H., Anderson, W. P., & Baetz, B. W. (1994). Environmental Input-Output Analysis and its Application to Regional Solid-waste Management Planning. In *Journal of Environmental Management* (Vol. 42, pp. 63–79). https://doi.org/10.1006/jema.1994.1061

Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., & Williams, P. T. (2017). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production*, *166*, 910–938. https://doi.org/10.1016/j.jclepro.2017.07.100

Jensen, C. D., Mcintyre, S., Munday, M., & Turner, K. (2013). Responsibility for Regional Waste Generation: A Single-Region Extended Input-Output Analysis for Wales. *Regional Studies*, *47*(6), 913–933. https://doi.org/10.1080/00343404.2011.599797

Kagawa, S., Kudoh, Y., Nansai, K., & Tasaki, T. (2008). The Economic and Environmental Consequences of Automobile Lifetime Extension and Fuel Economy Improvement: Japan's Case. *Economic Systems Research*, *20*(1), 3–28. https://doi.org/10.1080/09535310801890615

Kagawa, S., Nakamura, S., Kondo, Y., Matsubae, K., & Nagasaka, T. (2015). Forecasting Replacement Demand of Durable Goods and the Induced Secondary Material Flows: A Case Study of Automobiles. *Journal of Industrial Ecology*, *19*(1), 10–19. https://doi.org/10.1111/jiec.12184

Kagawa, S., Nansai, K., & Kudoh, Y. (2009). Does product lifetime extension increase our income at the expense of energy consumption? *Energy Economics*, *31*(2), 197–210. https://doi.org/10.1016/j.eneco.2008.08.011

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kondo, Y., & Nakamura, S. (2004). Evaluating alternative life-cycle strategies for electrical appliances by the waste input-output model. *The International Journal of Life Cycle Assessment*, *9*(4), 236–246. https://doi.org/10.1007/BF02978599

Kondo, Y., & Nakamura, S. (2005). Waste input–output linear programming model with its application to eco-efficiency analysis. *Economic Systems Research*, *17*(4), 393–408. https://doi.org/10.1080/09535310500283526

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., Boland, J., Daniels, P., Dey, C., Fry, J., Hadjikakou, M., Kenway, S., Malik, A., Moran, D., Murray, J., Nettleton, S., Poruschi, L., Reynolds, C., Rowley, H., … West, J. (2014). Compiling and using input-output frameworks through collaborative virtual laboratories. *Science of the Total Environment*, *485–486*(1), 241–251. https://doi.org/10.1016/j.scitotenv.2014.03.062

Lenzen, M., & Reynolds, C. J. (2014). A Supply-Use Approach to Waste Input-Output Analysis. *Journal of Industrial Ecology*, *18*(2), 212–226. https://doi.org/10.1111/jiec.12105

Lenzen, M., & Rueda-Cantuche, J. M. (2012). A note on the use of supply-use tables in impact analyses. *SORT*, *36*(2), 139–152. https://doi.org/http://www.idescat.cat/sort/sort362/36.2.2.lenzen-cantuche.pdf

Li, J., Lin, C., & Huang, S. A. (2013). Considering Variations in Waste Composition during Waste Input-Output Modeling. *Journal of Industrial Ecology*, *17*(6), 892–899. https://doi.org/10.1111/jiec.12068

Liao, M. I., Chen, P. C., Ma, H. W., & Nakamura, S. (2015). Identification of the driving force of waste generation using a high-resolution waste input-output table. *Journal of Cleaner Production*, *94*, 294–303. https://doi.org/10.1016/j.jclepro.2015.02.002

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lin, C. (2011). Identifying Lowest-Emission Choices and Environmental Pareto Frontiers for Wastewater Treatment Wastewater Treatment Input-Output Model based Linear Programming. *Journal of Industrial Ecology*, *15*(3), 367–380. https://doi.org/10.1111/j.1530-9290.2011.00339.x

Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology*, *00*(0), 1–14. https://doi.org/10.1111/jiec.12552

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., & Doménech, T. (2017). Circular Economy Policies in China and Europe. *Journal of Industrial Ecology*, *21*(3), 651–661. https://doi.org/10.1111/jiec.12597

McKinsey&Company. (2016). *The circular economy: Moving from theory to practice* (Issue October). http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-circular-economy-moving-from-theory-to-practice

Merciai, S., & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *00*(0), 1–16. https://doi.org/10.1111/jiec.12713

Miller, R. E., & Blair, P. D. (2009). *Input–Output Analysis: Foundations and Extensions* (Second edi). Cambridge University Press.

Murray, A., Skene, K., & Haynes, K. (2015). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*, 369–380. https://doi.org/10.1007/s10551-015-2693-2

Nakajima, K., Ohno, H., Kondo, Y., Matsubae, K., Takeda, O., Miki, T., Nakamura, S., & Nagasaka, T. (2013). Simultaneous Material Flow Analysis of Nickel, Chromium, and Molybdenum Used in Alloy Steel by Means of Input–Output Analysis. *Environmental Science & Technology*, *47*(9), 4653–4660. https://doi.org/10.1021/es3043559

Nakamura, Kondo, Y., Kagawa, S., Matsubae, K., Nakajima, K., & Nagasaka, T. (2014). MaTrace: Tracing the Fate of Materials over Time and Across Products in Open-Loop Recycling. *Environmental Science & Technology*, *48*(13), 7207–7214. https://doi.org/10.1021/es500820h

Nakamura, Nakajima, K., Kondo, Y., & Nagasaka, T. (2007). The waste input-output approach to materials flow analysis - Concepts and application to base metals. *Journal of Industrial Ecology*, *11*(4), 50–63. https://doi.org/10.1162/jiec.2007.1290

Nakamura, S. (1999). Input-output analysis of waste cycles. *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 475–480. https://doi.org/10.1109/ECODIM.1999.747659

Nakamura, S. (1999). An interindustry approach to analyzing economic and environmental effects of the recycling of waste. *Ecological Economics*, *28*(1), 133–145. https://doi.org/10.1016/S0921-8009(98)00031-7

Nakamura, S, & Kondo, Y. (2006). A waste input–output life-cycle cost analysis of the recycling of end-of-life electrical home appliances. *Ecological Economics*, *57*, 494–506. https://doi.org/10.1016/j.ecolecon.2005.05.002

Nakamura, S, & Kondo, Y. (2009). *Waste Input-Output Analysis: Concepts and Application to Industrial Ecology*. Springer.

Nakamura, S, & Nakajima, K. (2005). Waste Input-Output Material Flow Analysis of Metals in the Japanese Economy. *MATERIALS TRANSACTIONS*, *46*(12), 2550–2553. https://doi.org/10.2320/matertrans.46.2550

Nakamura, S, Nakajima, K., Kondo, Y., & Nagasaka, T. (2007). The Waste Input-Output Approach to Materials Flow Analysis. *Journal of Industrial Ecology*, *11*(4), 50–63. https://doi.org/10.1162/jiec.2007.1290

Nakamura, S, Nakajima, K., Yoshizawa, Y., Matsubae-Yokoyama, K., & Nagasaka, T. (2009). Analyzing Polyvinyl Chloride in Japan With the Waste Input-Output Material Flow Analysis Model. *Journal of Industrial Ecology*, *13*(5), 706–717. https://doi.org/10.1111/j.1530-9290.2009.00153.x

Nakamura, Shinichiro, & Kondo, Y. (2002). Input-Output Analysis of Waste Management.

Journal of Industrial Ecology, *6*(1), 39–63. https://doi.org/10.1162/108819802320971632

Nishijima, D. (2017). The role of technology, product lifetime, and energy efficiency in climate mitigation: A case study of air conditioners in Japan. *Energy Policy*, *104*, 340–347. https://doi.org/10.1016/j.enpol.2017.01.045

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Fukushima, Y., & Nagasaka, T. (2017). Optimal Recycling of Steel Scrap and Alloying Elements : Input- Output based Linear Programming Method with Its Application to End-of-Life Vehicles in Japan. *Environ. Sci. Technol*, *51*(22), 13086–13094. https://doi.org/10.1021/acs.est.7b04477

Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S., & Nagasaka, T. (2014). Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles. *Journal of Industrial Ecology*, *18*(2), 242–253. https://doi.org/10.1111/jiec.12095

Ohno, H., Nuss, P., Chen, W. Q., & Graedel, T. E. (2016). Deriving the Metal and Alloy Networks of Modern Technology. *Environmental Science and Technology*, *50*(7), 4082–4090. https://doi.org/10.1021/acs.est.5b05093

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*(October 2017), 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Pauliuk, S., Kondo, Y., Nakamura, S., & Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. *Resources, Conservation and Recycling*, *116*, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029

Pearce, D., & Turner, R. (1990). *Economics of natural resources and the environment*. Harvester Wheatsheaf.

Peters, G. P., & Hertwich, E. G. (2009). The Application of Multi-regional Input-Output Analysis to Industrial Ecology. In S. Suh (Ed.), *Handbook of Input-Output Economics in Industrial Ecology* (pp. 847–848). Springer.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product Chain*. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Pratt, K., & Lenaghan, M. (2015). *The Carbon Impacts of the Circular Economy Technical Report*. http://www.zerowastescotland.org.uk/sites/default/files/CIoCE Technical Report - FINAL - 15.06.15.pdf

Reutter, B., Lant, P., Lane, J., Reynolds, C., & Reynolds, C. (2017). Food waste consequences: Environmentally extended input-output as a framework for analysis. *Journal of Cleaner Production*, *153*, 506–514. https://doi.org/10.1016/j.jclepro.2016.09.104

Reynolds, C., Geschke, A., Piantadosi, J., & Boland, J. (2016). Estimating industrial solid waste and municipal solid waste data at high resolution using economic accounts: an input–output approach with Australian case study. *Journal of Material Cycles and Waste Management*, *18*(4), 677–686. https://doi.org/10.1007/s10163-015-0363-1

Reynolds, C. J., Piantadosi, J., & Boland, J. (2014). A Waste Supply-Use Analysis of Australian Waste Flows. *Journal of Economic Structures*, *3*(1), 5. https://doi.org/10.1186/s40008-014-0005-0

Reynolds, C. J., Piantadosi, J., & Boland, J. (2015). Rescuing food from the organics waste stream to feed the food insecure: An economic and environmental assessment of australian food rescue operations using environmentally extended waste input-output analysis. *Sustainability*, *7*, 4707–4726. https://doi.org/10.3390/su7044707

Reynolds, C., Mirosa, M., & Clothier, B. (2016). New Zealand's Food Waste: Estimating the Tonnes, Value, Calories and Resources Wasted. *Agriculture*, *6*(1), 9. https://doi.org/10.3390/agriculture6010009

Rodrigues, J. F. D., Lorena, A., Costa, I., Ribeiro, P., & Ferrão, P. (2016). An Input-Output Model of Extended Producer Responsibility. *Journal of Industrial Ecology*, *20*(6), 1273–1283. https://doi.org/10.1111/jiec.12401

Salemdeeb, R., Al-tabbaa, A., & Reynolds, C. (2016). The UK waste input – output table: Linking waste generation to the UK economy. *Waste Management & Research*, *34*(10), 1089–1094. https://doi.org/10.1177/0734242X16658545

Shigetomi, Y., Nansai, K., Kagawa, S., & Tohno, S. (2015). Trends in Japanese households' critical-metals material footprints. *Ecological Economics*, *119*, 118–126. https://doi.org/10.1016/j.ecolecon.2015.08.010

Skelton, A. C. H., & Allwood, J. M. (2013). The incentives for supply chain collaboration to improve material efficiency in the use of steel: An analysis using input output techniques. *Ecological Economics*, *89*, 33–42. https://doi.org/10.1016/j.ecolecon.2013.01.021

Takase, K., Kondo, Y., & Washizu, A. (2005). An analysis of sustainable consumption by the waste input-output model. *Journal of Industrial Ecology*, *9*(1–2), 201–219. https://doi.org/10.1162/1088198054084653

Takeyama, K., Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., & Nagasaka, T. (2016). Dynamic material flow analysis of nickel and chromium associated with steel materials by using matrace. *Matériaux & Techniques*, *104*(6–7), 610. https://doi.org/10.1051/mattech/2017012

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. *Journal of Industrial Ecology*, *00*(0), 1–13. https://doi.org/10.1111/jiec.12562

Tsukui, M., Ichikawa, T., & Kagatsume, M. (2017). Repercussion effects of consumption by domestic tourists in Tokyo and Kyoto estimated using a regional waste input – output approach. *Journal of Economic Structures*, 1–17. https://doi.org/10.1186/s40008-017-0061-3

Tsukui, M., Kagawa, Shigemi, & Kondo, Y. (2011). Urban growth and waste management optimization towards 'zero waste city.' *City, Culture and Society*, *2*(4), 177–187. https://doi.org/10.1016/j.ccs.2011.11.007

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2016). Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environmental Change*, *40*, 171–181. https://doi.org/10.1016/j.gloenvcha.2016.07.002

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J. M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., & Kuenen, J. (2013). Exiopol – Development and Illustrative Analyses of a Detailed Global Mr Ee Sut/Iot. *Economic Systems Research*, *25*(1), 50–70. https://doi.org/10.1080/09535314.2012.761952

Tukker, A., & Dietzenbacher, E. (2013). Global Multiregional Input – Output Frameworks : An introduction and outlook Global Multiregional Input – Output. *Economic Systems Research*, *25*(1), 1–19. https://doi.org/10.1080/09535314.2012.761179

WEF. (2014). Towards the Circular Economy : Accelerating the scale-up across global supply chains. In *World Economic Forum*. https://doi.org/10.1162/108819806775545321

Weisz, H., & Duchin, F. (2006). Physical and monetary input-output analysis: What makes the difference? *Ecological Economics*, *57*(3), 534–541. https://doi.org/10.1016/j.ecolecon.2005.05.011

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*(2), 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *PNAS*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825–833. https://doi.org/10.1016/j.rser.2016.09.123

Winning, M., Calzadilla, A., Bleischwitz, R., & Nechifor, V. (2017). Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. *International Economics and Economic Policy*. https://doi.org/10.1007/s10368-017-0385-3

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14*, 1–10. https://doi.org/10.1145/2601248.2601268

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., & Tukker, A. (2015). Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, *7*(1), 138–163. https://doi.org/10.3390/su7010138

Yokoyama, K., Onda, T., Kashiwakura, S., & Nagasaka, T. (2006). Waste Input-Output Analysis on Landfill Mining Activity. *Materials Transactions*, *47*(10), 2582–2587. https://doi.org/10.2320/matertrans.47.2582

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *In Press*(0), 1–10. https://doi.org/10.1111/jiec.12545

Chapter 3

The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011

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Aguilar-Hernandez, G.A., C.P. Sigüenza-Sanchez, F. Donati, Merciai, S, Schmidt, J, J.F.D. Rodrigues, and A. Tukker. 2018. Corrigendum to "The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011". [Resour. Conserv. Recy. 151 (2019) 104452]. https://doi.org/10.1016/j.resconrec.2019.104604

Abstract

Due to increased policy attention on circular economy strategies, many studies have quantified material use and recovery at national and global scales. However, there has been no quantitative analysis of the unrecovered waste that can be potentially reintegrated into the economy as materials or products. This can be interpreted as the gap of material circularity. In this chapter we define the circularity gap of a country as the generated waste, plus old materials removed from stocks and durable products disposed (i.e. stock depletion), minus recovered waste. We estimated the circularity gap of 43 nations and 5 rest of the world regions in 2011, using the global, multiregional hybrid-units input-output database EXIOBASE v3.3. Our results show the trends of circularity gap in accordance to each region. For example, the circularity gaps of Europe and North America were between 1.6-2.2 tonnes per capita (t/cap), which are more than twice the global average gap (0.8 t/cap). Although these regions presented the major amount of material recovery, their circularity gaps were mostly related to the levels of stock depletion. In Africa and Asia-Pacific regions, the circularity gap was characterized by a low degree of recovery and stock depletion, with high levels of generated waste. Moreover, we discuss which intervention types can be implemented to minimize the circularity gap of nations.

Keywords: Circular economy, multiregional hybrid-units input-output tables, material-based metrics, circularity interventions, resource efficiency

3.1. Introduction

Ensuring well-being within the planetary boundaries has become a prominent issue in the worldwide political agenda. Within this context the circular economy has emerged as a paradigm that promotes economic and environmental sustainability (Abadia et al., 2018; Geissdoerfer et al., 2017; Winans et al., 2017).

Several governments have adopted the circular economy as a key component in resource efficiency and sustainability strategies (Ghisellini et al., 2016; Iacovidou et al., 2017; McDowall et al., 2017; Zengwei Yuan, Jun Bi & S, 2006). Furthermore, to support these policies and identify priority areas in which circularity actions can be implemented effectively, it is important to quantify the degree of circularity of different products and materials (see, for example, Bastein et al., 2013; EMF, 2017; Su et al., 2013).

With the current policy interest in circularity actions, there is a growing body of literature that investigates recovery and waste generation at country and regional levels (Geng et al., 2012; Murray et al., 2015). The resulting data constitute a fundamental tool for monitoring the cost-effectiveness of circular economy strategies (Haupt et al., 2016; Mayer et al., 2018; Pauliuk, 2018). We will now review the main findings of these studies.

Haas et al. (2015) provided an overview of the circularity degree of the global economy and Europe in 2005. The researchers assessed the global material circularity by measuring the ratio between waste recovery and domestic material input (the latter defined as the sum of domestic material extraction and imports). Their outcomes showed a low degree of material circularity worldwide. The low circularity of materials was explained by two main factors: 44% of resources are used for energy purposes, and almost 30% of extracted materials are accumulated as in-use stocks (i.e. material for buildings, infrastructure, and products with long lifespan). They argued that this is a major limitation for the potential of recycling as a key strategy to increase material circularity, given that there are strong technological limitations to the extent that energy products and in-use stock materials can be recirculated.

Several studies have assessed the circularity degree at country and regional levels using the economic-wide material flow analysis (EW-MFA) as a consistent framework to analyze recirculated materials (Jacobi et al., 2018; Kovanda, 2014; Krausmann et al., 2018; Mayer et al., 2018; Nuss et al., 2017; van Eygen et al., 2017). For instance, Nuss et al. (Nuss et al., 2017) applied the EW-MFA approach to identify the material circularity for individual member states of the European Union. Their findings are similar to those reported by Haas et al. (2015), in which a low degree of material circularity per country resulted from the use of materials for energy consumption and stock accumulation.

Pauliuk and colleagues (2017) calculated the material circularity using a dynamic input-output material flow model that considers explicitly material losses and quality. The researchers analyzed the steel scrap accumulation through different economic activities over one hundred years from vehicles in Japan, Germany and United States. They studied multiple end-of-life scenarios taking a baseline scenario with present loss rates, trade trends, and scrap waste treatment through electric arc furnace. The authors demonstrated that the baseline scenario has a circularity degree of 87%, which refers to the accumulation of steel (in tonnes) between 2015 and 2100 respect to the theoretical maximum accumulative value.

Shortly after, Nakamura et al. (2017) quantified the recycling rate and losses of alloying metals in the Japanese steel cycle. They applied a cumulative sum for the use of materials over certain time, called cumulative service index. Their findings showed that more than 70% of alloying metals, namely chromium and nickel, can be retained by the Japanese economy under a scenario of high-level scrap sorting. Together these studies, Pauliuk et al. (2017) and Nakamura et al. (2017), recognized the role of product lifetime extension and recycling rates into the analysis of material circularity.

By exploring theoretical physical limits, Cullen (2017) estimated the material recovery and energy requirements of five resource categories: steel, concrete, plastic, paper and aluminum. He proposed a material circularity index that consists in the product of two ratios, recovered materials and energy requirements: recovered materials were defined as the fraction of end-of-life materials that are recovered divided by the primary material inflow; energy requirements were defined as the proportion of the energy needed in products from recovered or recycled materials, called secondary production, as a fraction of products from virgin materials (i.e. primary production). In his approach, the degree of material circularity varied depending on the type of material. For instance, the circularity index indicated values from 4% in the case of paper to 20% for aluminum. The author suggested that the remaining percentage of the circularity index can be used as a theoretical value of the circularity potential of a material.

In a similar way, Fellner et al. (2017) determined the potential of circular economy strategies in Europe. They quantified the amount of waste that is not recovered and can be used in the future by recycling activities. The researchers also estimated the potential economic gains and reductions in carbon emissions if waste fractions that were not recovered could be transformed into secondary raw material for replacing primary resources. Their findings were similar to those reported by Haas et al. (2015), in which a limited potential of material circularity was resulted from the amount of materials that are part of the in-use stocks.

In a recent technical report, de Wit et al. (2018) quantified the global gap of material circularity for 2015. The authors first estimated the degree of circularity worldwide considering the percent share of recovered materials as part of the total resource extraction. They determined that global material circularity was less than 10% and concluded that a theoretical gap of around 90% can potentially be recovered.

When these studies are taken into consideration, it can be noticed that the current analysis of material circularity is mostly focused on how much waste is recovered in an economy as shares of primary material inputs. Furthermore, the current metric of circularity gap does not distinguish between the amount of materials that are emitted, added to stocks, or disposed as waste from previous in-use stocks. This last aspect limits the capacity to identify the actual waste available for circularity because the current measurement accounts for waste materials that are not available to be recovered in the present.

To enhance the circularity gap calculation, we propose a metric that focuses on the amount of unrecovered waste that can be reintegrated into the economy as materials or products. A key difference between our approach and the previous studies is that we make an explicit mathematical distinction between those materials that are added to stocks and dispersed in the environment as dissipative emissions or other combustion and biomass residues. This allows us to identify the actual fraction of waste for material circularity in a specific period. We consider the quantity of waste generated and recovered in a period, and the old goods removed from stock and durable products disposed, defined as stock depletion (EC, 2001; J. Schmidt et al., 2013a). Thus, the circularity gap (CG) of a nation can be defined from these parameters as the waste generation, plus stock depletion, minus recovered materials. Such a CG metric can be seen as measure of the waste materials that are theoretically available for circularity.

In this chapter, we aim to determine the CG of nations considering waste generation, recovery, and stock depletion. We calculate the CG of 43 countries and 5 rest of the world regions in 2011, using the global multiregional hybrid-units input-output database EXIOBASE v3 (Stadler et al., 2018; Tukker et al., 2013, 2018; Wood et al., 2015). We then discuss in which way the CG of a specific country or region can be minimized through four intervention categories described in Chapter 2: product lifetime extension, closing supply chain, resource efficiency, residual waste management (Aguilar-Hernandez et al., 2018). To the best of our knowledge, this is the first study that calculates and compares the gap of material circularity for 43 nations and 5 global regions in a consistent framework.

The chapter is organized as follows: Section 3.2 describes the data and methods. Section 3 then shows the findings of the analysis. Sections 3.4 and 3.5 bring a discussion from the main finding, and final remarks.

3.2. Data and methods

In this section we report the process undertaken to quantify the circularity gap (CG) of nations. First, we define the system's boundaries for the input-output material flows of an economy. Second, we present the calculations to obtain the CG of nations considering the amount of generated waste, stock depletion, and recovered materials. Finally, we describe the EXIOBASE v3.3 database and its elements used in our analysis.

3.2.1. System definition

A generic diagram of the material flows in an economy is presented in figure 3.1 (Nuss et al., 2017; J. Schmidt et al., 2013a). In the diagram, the following activities (represented as solid boxes) are considered: intermediate activities and final demand (I&C), waste treatment sectors (T), and rest of the world economy (RoW). Material stocks (presented as solid circles) are considered: stock of natural resources (N), material in-use stocks (S), and the stock of nature from domestic processed outputs (DPO). The last one comprises all material wastes that are disposed into the environment as dissipative emissions or other combustion and biomass residues (e.g. ashes and slag from fossil fuels combustion, and biomass waste from humans and livestock), as well as waste solid landfilling and incineration. The following flows (represented as solid lines) are considered: imports (m), domestic resource extraction (r), recovered or secondary materials (w_{rec}), exports (e), waste generation (w_{sup}), additions to stocks (s_{add}), stock depletion (s_{dep}). Finally, the flow of dissipative emissions, and other combustion and biomass residues caused by intermediate activities and final demand ($b_{I\&C}$), and waste treatment (b_T) are represented as dashed lines. Waste treatment is considered as a defensive expenditure that can be required to mitigate the potential impacts of waste disposal on the environment (EC, 2000). Considering a system boundary for the global economy, figure 1 is adapted by deleting m and e flows, and RoW sectors due to physical trade balance to other regions (i.e. exports minus imports flows) does not occur in this context (EC, 2001).

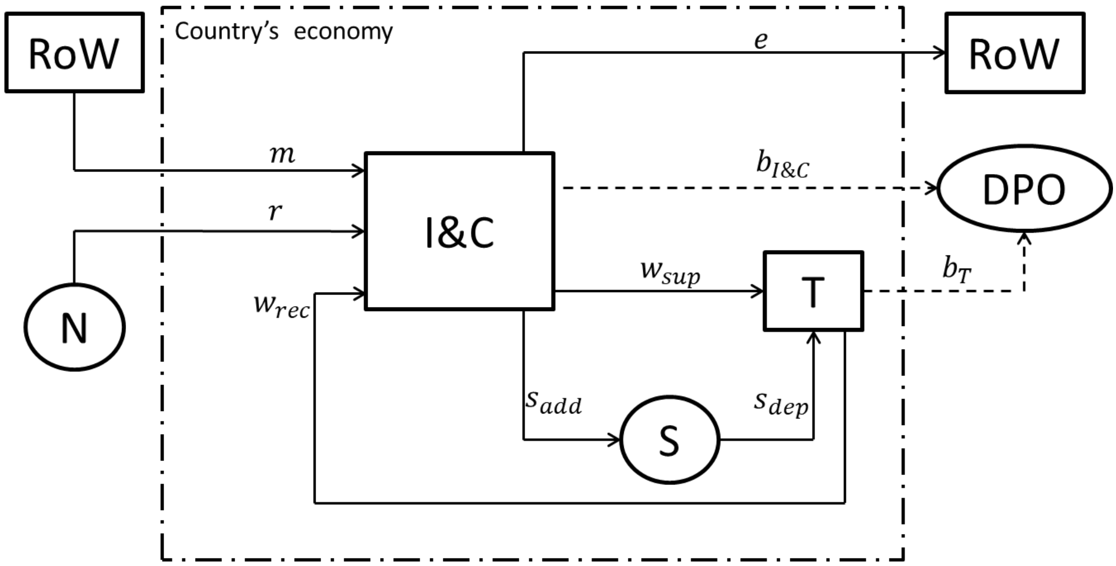

Figure 3.1. System definition of the input-output material flows of a country. Solid blocks indicate economic activities of: I&C = Intermediate sectors and final demand; T = waste treatment activities; RoW = Rest of the world. Solid circles indicate resource stocks of: N = Natural resources; S = Material in-use stocks; DPO = Domestic processed output. Solid and dashed lines indicate flows of: m = imports; r = resource extraction domestically; w_{rec} = waste recovery; e = exports; s_{add} = stock additions; s_{dep} = stock depletion, w_{sup} = waste generation; $b_{I\&C}$ = dissipative emissions, others combustion and biomass residues from intermediate activities and final demand; and b_T = dissipative emissions and others combustion and biomass residues from waste treatment.

3.2.2. Circularity gap calculation

For a specific period, there are three main outflows related to the amount of waste materials that can be potentially recovered as physical products: waste generation, stock depletion, and waste recovery. First, waste generation or supply (w_{sup}) represents the material/product outflows of human activity which require further treatment to be disposed of outside the technosphere (Merciai & Schmidt, 2018; J. Schmidt et al., 2013a). Second, stock depletion (s_{dep}) expresses the amount of waste resulting from materials accumulated previously, which includes the old materials depleted from stock and durable products disposed from previous years (EC, 2001; J. Schmidt et al., 2013a; J. Schmidt & Merciai, 2017). Third, waste recovery (w_{rec}) refers to all waste that is reprocessed or recycled into products or materials that are used by the economy (Haas et al., 2015; Jacobi et al., 2018). Thus, the circularity gap (CG) can be defined as all waste that is generated (from w_{sup} ands_{dep}) excluding the recovered waste (w_{rec}). That is, CG can be expressed as follows:

$$CG = w_{sup} + s_{dep} - w_{rec} \,. \quad [3.1]$$

We now use CG to express the material balance of intermediate activities and final demand (I&C), and waste treatment sectors (T). From figure 1, I&C is mathematically expressed as:

$$m + r + w_{rec} = e + b_{IC} + w_{sup} + S_{add}, \quad [3.2]$$

$$r = (e - m) + b_{IC} + \left(w_{sup} + S_{dep} - w_{rec}\right) + \left(S_{add} - S_{dep}\right), \quad [3.3]$$

in which $(e - m) = trade$ denotes the physical trade balance, $\left(S_{add} - S_{dep}\right) = NAS$ represents net additions to stocks. Thus, I&C material balance can be expressed as follows:

$$r = trade + b_{IC} + CG + NAS, \quad [3.4]$$

where $trade = 0$ in the case of global material balance.

In a similar way, the material balance of waste treatment sectors (T) can be represented as:

$$w_{sup} + S_{dep} = w_{rec} + b_T \Leftrightarrow w_{sup} + S_{dep} - w_{rec} = b_T \Leftrightarrow CG = b_T. \quad [3.5]$$

It is important to notice that CG represents a simplification of the time dimension and material losses. Regarding the temporal aspect, waste recovery consists of waste materials from the same period as well as those released as waste from preview years due to stock depletion (J. Schmidt et al., 2013b). In this study, it is assumed that waste generation, stock depletion, and recovery take place in the same year, and future waste supply is the result from additions to stocks. In addition, this approach does not recognize material losses, quality, or recycling efficiency rates.

Our CG metric is based on the circularity definition proposed by Cullen (2017), Fellner et al. (2017), and Wit et al. (2018). These studies focused on a material-oriented approach where the recovered waste is considered a circular material, and the material gap results from all materials that are not recovered in a specific period. Nevertheless, this could lead to misunderstand a circular economy as a system with zero dissipative emissions and unchanged stocks, which is rather an unrealistic and optimistic outlook of material flows. In order to avoid such a material outlook, we consider the CG only from the materials that pass through waste treatment sectors and are not reintegrated into the economy. Thus, CG can be considered as the theoretical amount of waste that is not used in a circular way.

Following previous material circularity approaches (de Wit et al., 2018; Haas et al., 2015; Mayer et al., 2018), the circularity index (CI) for a specific country or region can be expressed as:

$$CI = \frac{w_{rec}}{r + m} \times 100, \quad [3.6]$$

in which $r + m$ denotes the domestic material input of intermediate activities and final demand (I&C). Similarly, we can represent a circularity gap index (CGI) of a nation as follows:

$$CGI = \frac{CG}{w_{sup} + s_{dep}} \times 100, \quad [3.7]$$

$$CGI = \frac{CG}{(w_{sup} + s_{dep} - w_{rec}) + w_{rec}} \times 100 \Leftrightarrow CGI = \frac{CG}{CG + w_{rec}} \times 100. \quad [3.8]$$

3.2.3. Global, multiregional hybrid input-output table from EXIOBASE v3.3.

Data from the global, multiregional hybrid-units input-output table (MR-HIOTs) EXIOBASE version 3.3.15. was used to estimate the CG of 43 countries and 5 rest of the world regions in 2011 (Stadler et al., 2018; Tukker et al., 2013; Wood et al., 2015). The transactions shown in the database are expressed in mixed units: tonnes for physical values, euros for economic terms, and terajoules for energy (Merciai & Schmidt, 2018). We performed the CG calculation using the EXIOBASE v3.3.15 extension accounts of waste supply and use, stock additions and depletion, emissions, and domestic material extraction.

Our CG approach strongly depends on the capacity of determining stock additions and depletion. It is important to notice that the hybrid units input-output approach differs from a traditional monetary input-output tables, where net additions to stocks are usually allocated to final demand categories as changes in inventories and fixed capital formation (Dietzenbacher, 2005; Eurostat, 2008; Hubacek & Giljum, 2003; Suh, 2004; Weisz & Duchin, 2006). Instead, the stock addition and depletion in MR-HIOTs EXIOBASE v3.3.15 are part of the material balance from the resources, dissipative emissions, and waste. The construction of stock addition account results from mass balance checks throughout 5 integrated sections, which comprise: agriculture, energy, technical coefficient, trade, and balancing modules (Geerken et al., 2019; Merciai & Schmidt, 2018; J. Schmidt & Merciai, 2017). In the same way described by Suh et al. (2010) and Eurostat (2013a) for physical input-output tables, stock additions in MR-HIOTs EXIOBASE v3.3.15 represents the actual material added to the economy's stocks, and stock depletion refers to materials removed from stock as demolished buildings, and disposed durable goods.

To identify waste recovery flows, we focused on 19 activities related to re-processing, recycling, biogasification, and composting products. Based on the Ellen MacArthur Foundation (EMF, 2013) and Bocken et al. (2016) material archetypes for circularity, we considered the energy recovery from waste incineration as an activity that leads to material leakage on an economy, and it should be minimized in a circular economy context. Thus, we did not include waste incineration as part of the material recovery sectors.

In order to visualize the input-output flows of materials and CG worldwide, we created a Sankey diagram based on the Economy-wide Material Loop Closing framework (Mayer et al., 2018). From MR-HIOTs EXIOBASE v3.3.15 extension accounts, we organized 39 resource extraction, 17 material waste, and 66 emission categories into four material groups: biomass, fossil fuels, metals, and nonmetallic minerals. Processed materials (including for energy and material use) are aggregated in the block of intermediate activities and final demand (I&C) as shown in Figure 3.1.

In MR-HIOTs EXIOBASE v3.3.15, the account of resources for agriculture includes the production of biomass residues (Schmidt & Merciai, 2017). Thus, we considered the residual crops supply as part of the biomass balance. Furthermore, we estimated the amount of unregistered waste per material category and allocated it to domestic processed output (DPO).

We did not include the extraction of oxygen from air and the water consumption of humans and livestock. To exclude these resources (oxygen and water) from the global mass balance, we applied the coefficients of relative mass to covert CO_2 emissions from the combustion of fossil and biogenic resources to the actual extracted carbon equivalent (see Schmidt et al., 2010). In a similar way, metals are measured in terms of the content of material in the respective ores. This means that we considered the coefficients of metal concentrates in ores excluding the amount of unused and mining waste. Furthermore, waste trade (or the shipment of waste as defined by Eurostat (2013b)) was not incorporated due to the lack of data on international waste trade (Schmidt et al., 2013a). Our results are presented in terms of dry matter content.

For comparing the national and regional CG's, we presented the CG calculation by region and in per capita terms. We retrieved the world's population and GDP-PPP (in 2011 current international US-dollars) datasets from the World Bank Open Data (2020), and integrated into the MR-HIOTs EXIOBASE v3.3.15 for 2011.

3.2.4. Cross-country, regression analysis

We performed a cross-country, regression analysis of CG and gross domestic product, purchasing power parity (GDP-PPP) per capita in order to analyze the relation between CG and income groups. Regression analysis has been applied to assess the link of material and waste generation with affluence across countries and regions (see, for example, Tisserant et al., 2017; Wiedmann et al., 2015). In a similar way, we expressed the relation between CG and GDP-PPP per capita category can be expressed as follows:

$$\mathrm{CG/cap} = \mathrm{k}(\mathrm{GDP/cap})^{\alpha}, \quad [3.10]$$

$$\log(CG/cap) = \log(\mathrm{k}) + \alpha\log(\mathrm{GDP/cap}), \quad [3.11]$$

where CG/cap represents the circularity gap per capita; GDP/cap denotes GDP-PPP per capita; α is the elasticity coefficient; and $\log(\mathrm{k}) = \beta$ is a constant parameter in the linear model. In this case, the elasticity α expresses the percentage change in CG/cap change as response to a 1% change in GDP-PPP/cap (Gujarati, 2003). We categorized each country and region by income group according to the World Bank Atlas method (2019).

Data source, a detailed list of resource/waste/emission classifications as well as the Python code used for the analysis can be found, in the online version, at doi: 10.5281/zenodo.1483548

3.3. Results

In 2011, the global economy required 74 Gigatonnes (Gt) of extracted materials (see figure 3.2). Total waste generation amounted to 9 Gt, of which 25% was from stock depletion and 75% from waste generated in the same period. Moreover, global material outputs were mostly allocated to stock additions (30 Gt), and directly dissipated as emissions or other combustion and biomass residues to the environment (40 Gt). These results are similar to those reported by material use studies, which reported values per year between 66-78 Gt of global material extraction, 30-36 Gt of stock additions, and 1-4 Gt of recovered solid waste in periods from 2007 to 2010 (Giljum et al., 2015; Krausmann et al., 2017; Tisserant et al., 2017; Weisz et al., 2006; Wiedmann et al., 2015). Likewise, we observe a low degree of material circularity for 2011, which is comparable to that described by Haas et al. (2015), and de Wit et al. (de Wit et al., 2018).

Regarding the circularity gap (CG) worldwide, there is around 6 Gt (or 0.8 tonnes per capita) of unrecovered waste that can be potentially reintegrated into the global economy as secondary materials or products. This value represents an 8% share of the global material extraction. We can see that the global CG in 2011 was relatively low compared to the material output that go to stock additions, and dissipative emissions and other combustion and biomass residues. Remarkably, the global economy presented a high level of stock accumulation from construction materials (90% of the total stock additions). Thus, without considering future waste generated from current additions to stocks, there was only a small fraction of unrecovered waste that could be potentially used for material circularity in 2011.

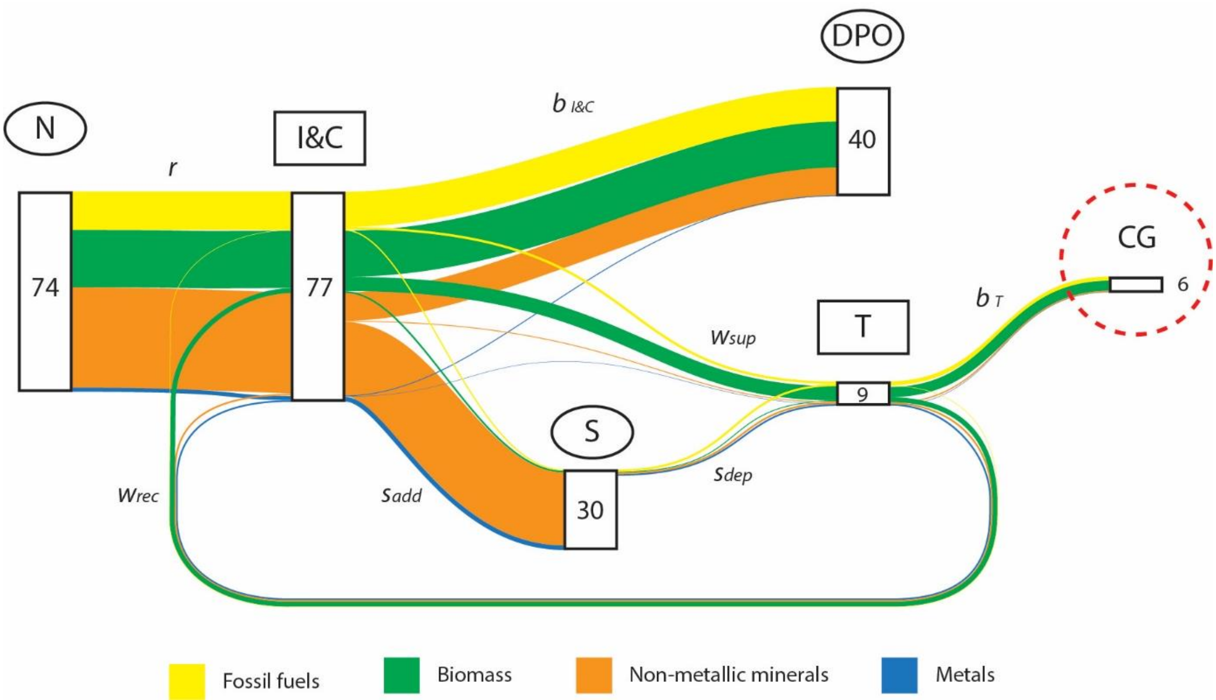

Figure 3.2. Sankey diagram of global material extraction, waste, and emission flows in 2011. Numbers indicate the size of flows in Gigatonnes (Gt). Solid blocks indicate economic activities of: I&C = Intermediate sectors and final demand; T = waste treatment activities. Solid circles indicate resource stocks of: N = Natural resources; S = Material in-use stocks; DPO = Domestic processed output. Colored lines indicate flows of: r = material extraction; w_{rec} = waste recovery; s_{add} = stock additions; s_{dep} = stock depletion, w_{sup} = waste generation; $b_{I\&C}$ = dissipative emissions, others combustion and biomass residues from intermediate activities and final demand; and b_T = dissipative emissions and others combustion and biomass residues from waste treatment. Dashed circle denotes circularity gap (CG). Note: RoW, m, and e are not shown in this figure because physical trade balance does not appear in the global material flow.

The global trend of material outputs also applied to specific countries and regions. Figure 3.3 presents the proportion of domestic processed output (DPO) in 5 countries and 6 aggregated regions (see 'exio_class' Excel file in supporting information for more details about the region categories). DPO comprises the sum of dissipative emissions, and other combustion and biomass residues caused by intermediate activities and final demand ($b_{I\&C}$), and the circularity gap (CG). In each country/region, more than 60% of DPO resulted from emissions and other residues to cause by intermediate activities and final consumption, especially for energy purposes. We observe that the material flow patterns are similar across countries and regions, where the circularity gap is minuscule compared to the sum of dissipative emissions and other combustion/biomass residues. For instance, the CG of Australia, Africa, Middle East and Asian-Pacific region constituted less than 10% of DPO in these nations.

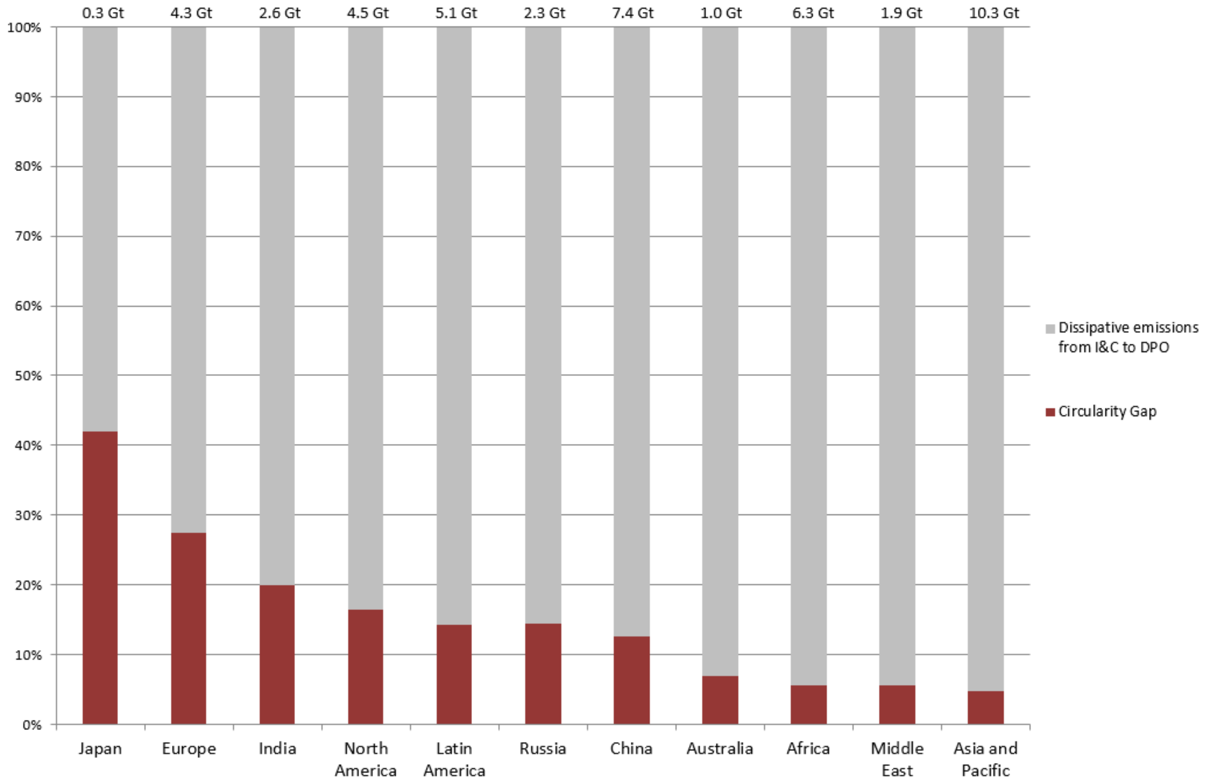

Figure 3.3. Composition of domestic processed output (DPO) for selected regions and countries in 2011. Upper values represent the sum of all material outputs (i.e. dissipative emissions, and other combustion and biomass residues caused by intermediate activities and final demand ($b_{I\&C}$), and the circularity gap (CG)) in Gigatonnes (Gt).

Table 3.1 presents a comparison of the traditional material gap expressed as 100 – Circularity Index (CI), and circularity gap index (CGI) for the selected regions and countries in 2011 (see equation [3.6] and [3.8] in method section). The new CGI allows to support the interpretation of traditional CI. For instance, the global CI in 2011 was around 4%, which represented the fraction of waste recovery compared to the total material input. Following the traditional approach (de Wit et al., 2018; Fellner et al., 2017), it would be interpreted that there was a material gap of 96% respect to total material input in 2011. However, this approach did not distinguish the fractions of material input that were added to stocks, and dispersed into the environment as dissipative emissions, and other residues from intermediate and final demand. Instead of a 96% global material gap, our CGI approach shows that around 62% of material wastes passed through waste treatment sectors, and were not reintroduced into the economy as recovered materials. The new CGI only considers the fraction of waste that is recovered and reintegrated into the economy, and, thus, it allows to determine the actual fraction of material waste that is not used in a circular manner.

Furthermore, a comparison of 100 – CI and CGI between countries/regions can bring insights about the structure of waste treatment activities in an economy. For instance, the traditional approach for material gap indicates that Japan generated less output of waste per unit of total material input (100 – CI=92%) compared to China (100 – CI=97%). In contrast, using the new CGI, our findings show that the fraction of residual waste generated by waste treatment activities in China (CGI=58%) was larger than in Japan (CGI=54%).

Table 3.1. Traditional material gap represented as 100 – Circularity Index (CI), and circularity gap index (CGI) for the world, and selected regions and countries in 2011

Region	100 – Circularity Index (CI) in %	Circularity Gap Index (CGI) in %
World	95.8	64.2
Japan	91.8	54.2
Europe	92.3	57.8
India	94.9	69.2
North America	96.0	69.9
Latin America	96.5	74.8
Africa	96.6	57.8
China	97.1	58.2
Australia	97.5	70.1
Russia	97.6	83.4
Asia and Pacific	98.1	64.7
Middle East	98.7	66.3

Turning now to the CG at national and regional levels, we identify the trends of unrecovered waste in each country or region. Figure 3.4 shows a breakdown (CG) organized by the selected countries and aggregated regions. CG results for 2011 all countries studied are provided in supplementary materials.

Europe showed the highest circularity gap in absolute values (1.2 Gt) and the fourth largest gap per capita (1.6 tonnes per capita, i.e., t/cap), even when European countries had the highest values of recovered waste (1.1 t/cap). Such CGs resulted from the high level of stock depletion that was five times larger than the global stock depletion average in 2011 (i.e. 0.3 t/cap). We observed similar trends in the CG of other high and upper middle income nations (for example, Japan, Australia, Russia, USA and Canada), where a major CG was presented in countries with a high level of waste recovery, but also larger stock depletion. In comparison with the global average (0.8 t/cap), the CG of these economies were between two and four times bigger than the CG worldwide.

In absolute terms, China had the second highest CG corresponding to 0.9 Gt for 2011. In this case, the Chinese economy recovered around 44% of the total waste available (1.6 Gt). While the amount of waste generation (1.0 t/cap) was slightly higher than world average, the depletion of stocks in China (0.2 t/cap) was similar to the values of medium and low income regions (less than 0.1 t/cap of stock depletion). The low degree of depleted stocks in China can be explained as a result of a phase of economic growth characterized by increasing stock accumulation (Krausmann et al., 2017, 2018), which was the trend of material flow for upper high income economies (such as Latin America region). Thus, we could expect an increment in future waste in China resulting from the erosion of present accumulated stocks (Schmidt & Merciai, 2017).

Africa, Middle East, and Asia-Pacific regions were characterized by a smaller CG, which presented an average of 0.4 t/cap. These regions also presented a common trend in terms of waste generation, recovery, and stock depletion. In comparison with the world average, middle to lower income nations showed lower values of stock depletion and recovered waste (less than 0.1 t/cap and 0.3 t/cap, respectively), with higher waste generation (between 0.4 and 0.6 t/cap). In general, most of the CG in middle, upper lower and lower income countries came from waste generation, which can be related to three aspects: a low capacity of residual waste management, the consumption of products with short lifetimes, and a growing of addition to stocks.

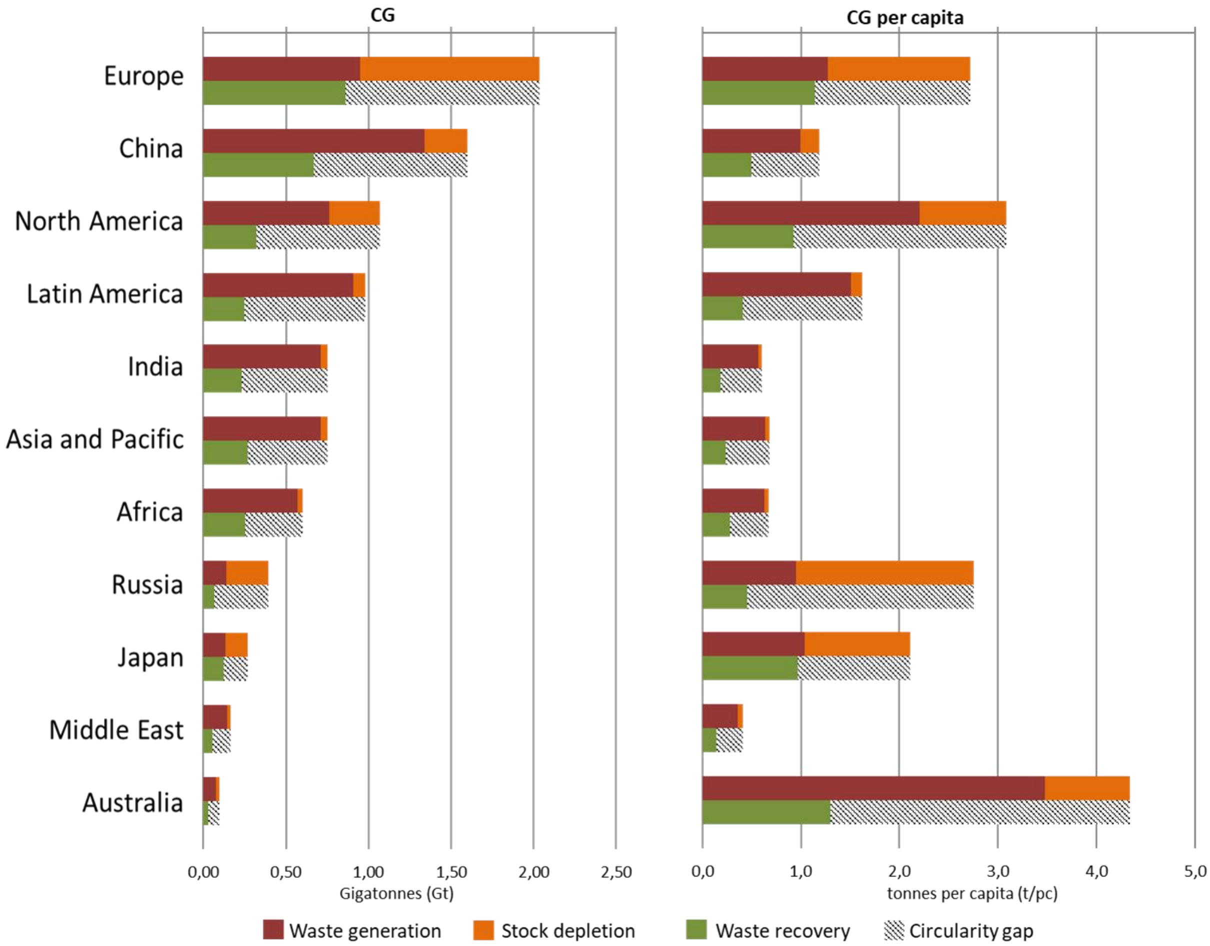

Figure 3.4. Circularity gap (CG, in totals and per capita) of selected regions and countries in 2011

Figure 3.5 presents the cross-country, regression analysis of CG and gross domestic product, purchasing power parity (GDP-PPP) per capita including all 43 countries and 5 rest of world regions in 2011 (see equation [3.11] in method section). This analysis shows that there is a positive relation between CG per capita and income groups, in which a change of 1.0% in GDP-PPP per capita would drive a change of 0.9% in CG per capita ($\alpha = 0.9$). Although the positive link between CG and GDP-PPP per capita, the correlation of both parameters is unclear ($R^2 = 0.272$). A low correlation coefficient of CG and GDP-PPP per capita can be explained by the differences of economic structure across regions, and a lack of data coverage in the database (Tisserant et al., 2017).

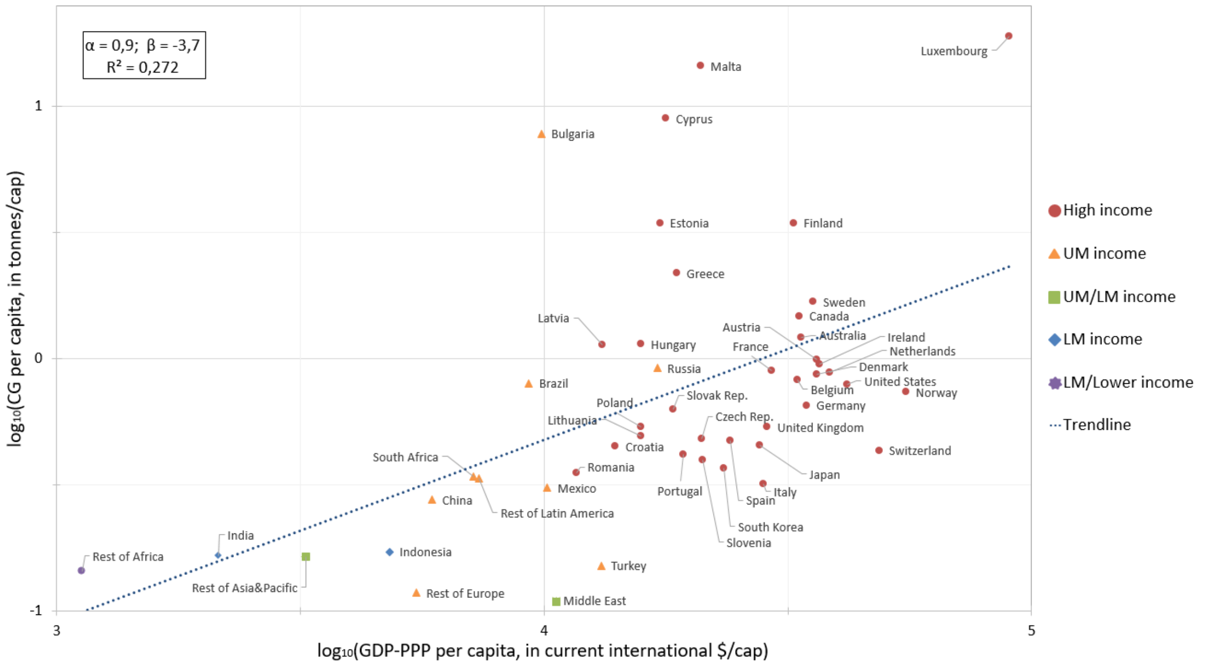

Figure 3.5. Logarithm of circularity gap per capita (CG/cap, in tonnes/cap) over logarithm of gross domestic product, purchasing power parity per capita (GDP-PPP/cap, in current international $/cap). Red circle indicates high income country. Orange triangle indicates upper middle income (UM income). Green square indicates upper middle and lower middle income (UM/LM income). Blue diamond indicates lower middle income (LM income). Purple 6-point star indicates lower middle and lower income (LM/Lower income). Dark blue dot line denotes the regression trendline, α is the elasticity, β is a constant parameter, and R^2 is the standard coefficient of determination.

3.4. Discussion

The purpose of this study was to estimate the circularity gap (CG) of countries, which in turns CG as generated waste, plus depleted stocks, minus recovered waste in a specific period. This CG metric allows to identify the trends of multiple regions, and the theoretical values of unrecovered waste that can be reintegrated as goods that substitute resource extraction. Moreover, our results may help us to understand which actions can be applied to contribute to circular economy policies. We now focus on interventions that can be implemented to enhance material circularity from changes in CG.

3.4.1. Opportunities of CG reduction through circularity interventions

In general, CG is a representation of the waste that can be potentially recovered for material circularity. Thus, we can expect an improvement of material circularity if a decrease of CG is made by a country/region. Considering the definition of CG used in this study, there are three ways to reduce a country's CG: increasing waste recovery, decreasing waste generation, and reducing stock depletion.

In order to change the material flows related to CG reduction (i.e. generated waste, depleted stocks, and recovered materials), specific circular economy strategies that aim to retain materials in a closed-loop economic system should be implemented (Blomsma & Brennan, 2017; Bocken et al., 2016; EMF, 2013; Geissdoerfer et al., 2017; Kirchherr et al., 2017). Such a set of strategies, also called circularity interventions, have been categorized in four groups: residual waste management, closing supply chains, resource efficiency, and product lifetime extension (see Table 2.1 in section 2.2., Chapter 2). In figure 3.6, we present a diagram that links the potential reduction of CG through the four circularity intervention types.

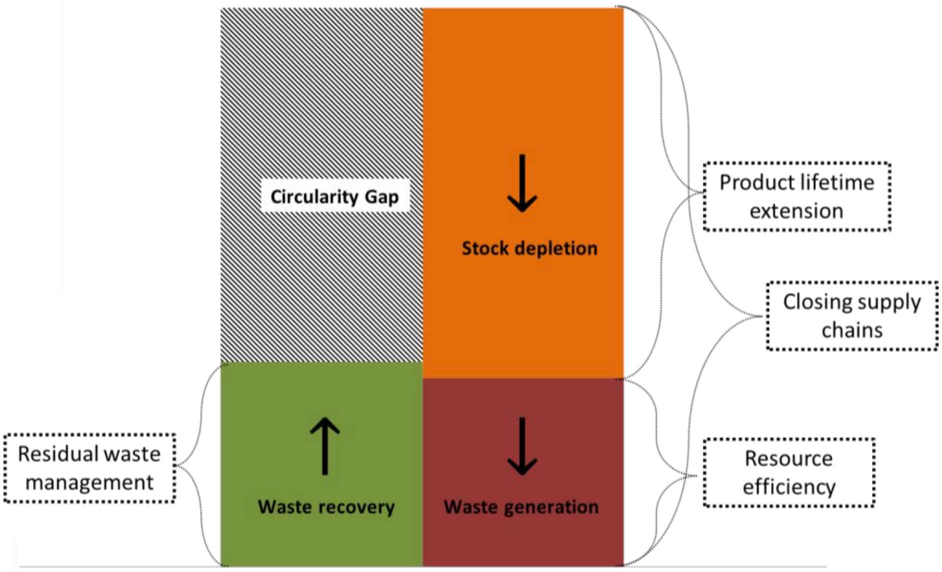

Figure 3.6. A circularity gap reduction through four intervention types. Green, red, and orange squares indicate material recovery, waste generation, and stock depletion, respectively. Area with black/white downward diagonal lines represents the circularity gap. White square with dots line border ('…') represents circularity intervention type. '↑' indicates an increase of material flow, '↓' indicates a decrease or delay of waste flow.

Waste recovery can be increased through residual waste management. This intervention type is focused on strategies at the end-of-life of products, in which materials are disposed outside the economic system (EMF, 2013; Kirchherr et al., 2017). An increase of waste recovery would imply the replacement of landfill and incineration processes with recycling activities. This can contribute to material circularity in countries with a low degree of waste recovery, which is particularly the case of middle, upper lower and lower income economies.

In terms of waste generation, there are two interventions that can be considered: closing supply chains, and resource efficiency. Closing supply chains are the strategies of re-integrating materials at different levels of the supply chain after their initial use phase. This intervention category is implemented by: using a product one more time for the same purpose (product reuse), taking reusable components and rebuilding a new product (component reuse), substituting or repairing major parts in order to return a product to its working condition (refurbishment), and material reuse as material recycling (EMF, 2013, 2017). Resource efficiency refers to actions that improve material flows through the use of less resources per unit of total output, which can contribute to waste reduction in specific activities (Bocken et al., 2016; Zhu et al., 2018). Together these interventions can contribute to decrease waste generation by improving material use. In fact, recent policies have been mostly focused on targets related to reducing waste as well as resource efficiency in high and upper high income countries, such as the circularity interventions proposed by European Union and China (see, for example, McDowall et al., 2017; Su et al., 2013; Zhu et al., 2018).

The decrease or delay of waste from previous stocks can be achieved through product lifetime extension. Such an intervention focuses on the design for longevity and maintenance of durable goods (Bocken et al., 2016; Kirchherr et al., 2017). It is expected that a significant amount of future waste will be generated due to the depletion in-use stocks from building and infrastructure activities, especially in high and upper high income countries, where there is a high degree of stock additions every year (Haas et al., 2015; Krausmann et al., 2017, 2018). Instead of interventions addressing material flows, delaying stock depletion should be focused on stock management, in which extending product lifetime will prevent the erosion of durable products (Stanhel & Clift, 2015). Likewise, it is important to notice that accumulated stocks and the time frame for future waste recovery should be considered as part of the intervention. On the other hand, closing supply chains can contribute to delaying stock depletion if the intervention of product life extension through product and component reuse is applied to extend the use phase of products.

3.4.2. Further steps

In this study the CG per country was calculated through a global multiregional hybrid-units input-output tables (MR-HIOTs). The MR-HIOTs have been recognized as a consistent framework for assessing circularity interventions at macro-scale (Aguilar-Hernandez et al., 2018; Tisserant et al., 2017). However, applying MR-HIOTs is restricted by model's staticity, the misrepresentation of feedback from nature to the economy, as well as the in-use stocks dynamics (de Koning, 2018; Wiedenhofer et al., 2019). Considering these limitations, three main elaborations for the future assessments of CG of nations follow.

First, estimating the actual generated waste from stock can be improved through dynamic MR-HIO model. This aspect would include materials that are becoming waste from previews years, as well as the time in which present waste will be released (J. Schmidt & Merciai, 2017). Likewise, a dynamic approach allows to evaluate resource duration and longevity (i.e. length of time a material is used), which are recognized as important factors for assessing circularity (Figge et al., 2018; Franklin-Johnson et al., 2016). Dynamic input-output and material flow models have been already developed (see, for example, Duchin & Levine, 2013; Pauliuk et al., 2017; Wiedenhofer et al., 2019), however, there is no estimation of CG related to the dynamic of stocks. Then, a more sophisticated metric should allow, for instance, to look at which potential use is made of lifetime extension, re-use and refurbishing of entire products or product components.

Second, to demonstrate whether the management of CG could contribute to separate environmental impacts from economic growth, assessing material circularity should reflect whether decoupling is achieved. Only recently a few studies have analyzed the impacts of resource use at global scale considering relative or absolute decoupling from nature (for example, Behrens et al., 2007; Schandl et al., 2016; Tukker et al., 2016; Wiedmann et al., 2015). These studies argue that the increase of international trade plays an important role on material efficiency and environmental sustainability, showing that environmental impacts have been offset from industrialized countries to emerging and low-income economies (Tukker et al., 2016; Wood et al., 2018). An assessment related to CG and the relation to decoupling could improve the understanding of potential environmental benefits generated by circularity transition.

Finally, MR-HIOTs should be enhanced in terms of waste accounts. At this moment, such accounting system is limited by a lack of information about waste and recovery international trades, and recognizing the quality of waste for future recovery fractions (Schmidt & Merciai, 2017). This implies that the actual CG can be lower than it is expected. Likewise, waste accounts do not include informal or illegal waste treatment sectors (Tisserant et al., 2017), which could affect the CG calculation by underestimating the actual gap.

Although further development is needed for assessing the full material capacity of a nation, this study allowed to identify the main factors of CG in a period and which interventions can be applied in a specific country or region. Moreover, we consider that the CG approach can be used as a starting point for discussing the meaning of the potential of material circularity at national and regional level, which can lead to best practices to quantify material CG and its potential for improving resource use.

3.5. Conclusions

This chapter estimated the circularity gap (CG) of nations by using MR-HIOTs from EXIOBASE v3.3 database. We identified the CG trends of 43 countries and 5 rest of the world regions in 2011. Furthermore, we discussed which intervention types can be applied in order to improve the material circularity of a country or region.

Further steps on assessing circularity potential are required in order to enhance the analysis. We recognized that major contributions can be developed by: considering the stocks' dynamic aspects; a relation between circularity, resource efficiency and decoupling; and accounting systems with international trades of waste and recovery. Together these aspects can be integrated into future research for bringing a better understanding on what would be the potential of a global circular economy from a material-based perspective.

3.6. References

Abadia, L. G., Carvalho, M. M., Homrich, A. S., & Galv, G. (2018). The circular economy umbrella: Trends and gaps on integrating pathways. *JOURNAL OF CLEANER PRODUCTION*, *175*, 525–543. https://doi.org/10.1016/j.jclepro.2017.11.064

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions : a review of EEIOA-based studies. *Journal of Economic Structures*, *7*(14), 1–24. https://doi.org/10.1186/s40008-018-0113-3

Bastein, T., Roelofs, E., Rietveld, E., & Hoogendoorn, A. (2013). Opportunities for a Circular Economy in the Netherlands. Technical Report. In *TNO*. https://doi.org/10.3390/en1030105

Behrens, A., Giljum, S., Kovanda, J., & Niza, S. (2007). The material basis of the global economy. Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. *Ecological Economics*, *64*(2), 444–453. https://doi.org/10.1016/j.ecolecon.2007.02.034

Blomsma, F., & Brennan, G. (2017). The Emergence of Circular Economy. A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology*, *21*(3), 603–614. https://doi.org/10.1111/jiec.12603

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Cullen, J. M. (2017). Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *Journal of Industrial Ecology*, *00*(0), 1–4. https://doi.org/10.1111/jiec.12599

de Koning, A. (2018). *Creating Global Scenarios of Environmental Impacts with Structural Economic Models* [Leiden University]. https://doi.org/ISBN: 978-94-90858-55-1

de Wit, M., Hoogzaad, J., Ramkumar, S., Friedl, H., & Douma, A. (2018). *The circularity gap report. An analysis of the circular state of the global economy. Technical Report*.

Dietzenbacher, E. (2005). Waste treatment in physical input-output analysis. *Ecological Economics*, *55*(1), 11–23. https://doi.org/10.1016/j.ecolecon.2005.04.009

Duchin, F., & Levine, S. H. (2013). Embodied Resource Flows in a Global Economy: An Approach for Identifying the Critical Links. *Journal of Industrial Ecology*, *17*(1), 65–78. https://doi.org/10.1111/j.1530-9290.2012.00498.x

EC. (2000). *Analysis of the fundamental concepts of resource management. Technical Report*.

EC. (2001). *Economy-wide material flow accounts and derived indicators. Technical Report*.

EMF. (2013). *Toward the circular economy. Technical Report*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

EMF. (2017). *Achieving Growth Within. Technical Report*.

Eurostat. (2008). Eurostat Manual of Supply, Use and Input-Output Tables. In *Methodologies and working papers, Economy and finance*. https://doi.org/http://ec.europa.eu/eurostat

Eurostat. (2013a). *Economy-wide Material Flow Accounts (EW-MFA) Compilation Guide 2013* (Issue July). http://ec.europa.eu/eurostat/web/environment/methodology

Eurostat. (2013b). Manual on waste statistics: A handbook for data collection on waste generation and treatment. In *Theme: Environment and energy Collection, Methodologies & Working papers*. https://doi.org/10.2785/51516

Fellner, J., Lederer, J., Scharff, C., & Laner, D. (2017). Present Potentials and Limitations of a Circular Economy with Respect to Primary Raw Material Demand. *Journal of Industrial Ecology*, *21*(3), 494–496. https://doi.org/10.1111/jiec.12582

Figge, F., Thorpe, A. S., Givry, P., Canning, L., & Franklin-johnson, E. (2018). Longevity and Circularity as Indicators of Eco-E fficient Resource Use in the Circular Economy. *Ecological Economics*, *150*, 297–306. https://doi.org/10.1016/j.ecolecon.2018.04.030

Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for Circular Economy performance. *JOURNAL OF CLEANER PRODUCTION*, *133*, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023

Geerken, T., Schmidt, J., Boonen, K., Christis, M., & Merciai, S. (2019). Assessment of the potential of a circular economy in open economies – Case of Belgium. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2019.04.120

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular

Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of Cleaner Production*, *23*, 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giljum, S., Bruckner, M., & Martinez, A. (2015). Material footprint assessment in a global input-output framework. *Journal of Industrial Ecology*, *19*(5), 792–804. https://doi.org/10.1111/jiec.12214

Gujarati, D. N. (2003). The Nature of Regression Analysis. In *Basic Econometrics* (Fourth Edi, pp. 17–24). McGraw-Hill.

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Haupt, M., Vadenbo, C., & Hellweg, S. (2016). Do We Have the Right Performance Indicators for the Circular Economy ? Insight into the Swiss Waste Management System. *Journal of Industrial Ecology*, *21*(3). https://doi.org/10.1111/jiec.12506

Hubacek, K., & Giljum, S. (2003). Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics*, *44*, 137–151. https://doi.org/10.1016/S0921-8009(02)00257-4

Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., & Williams, P. T. (2017). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production*, *166*, 910–938. https://doi.org/10.1016/j.jclepro.2017.07.100

Jacobi, N., Haas, W., Wiedenhofer, D., & Mayer, A. (2018). Providing an economy-wide monitoring framework for the circular economy in Austria : Status quo and challenges. *Resources, Conservation & Recycling*, *137*, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kovanda, J. (2014). Incorporation of recycling flows into economy-wide material flow accounting and analysis: A case study for the Czech Republic. *Resources, Conservation and Recycling*, *92*, 78–84. https://doi.org/10.1016/j.resconrec.2014.08.006

Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to out fl ows of wastes and emissions : The socioeconomic metabolism of the global economy , 1900 – 2015. *Global Environmental Change*, *52*, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., & Fishman, T. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS*, *114*(8), 21–26. https://doi.org/10.1073/pnas.1613773114

Mayer, A., Haas, W., Wiedenhofer, D., Nuss, P., & Blengini, G. A. (2018). Measuring Progress towards a Circular Economy A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, *00*(0), 1–15. https://doi.org/10.1111/jiec.12809

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., & Doménech, T. (2017). Circular Economy Policies in China and Europe. *Journal of Industrial Ecology*, *21*(3), 651–661. https://doi.org/10.1111/jiec.12597

Merciai, S., & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *00*(0), 1–16. https://doi.org/10.1111/jiec.12713

Murray, A., Skene, K., & Haynes, K. (2015). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*, 369–380. https://doi.org/10.1007/s10551-015-2693-2

Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., & Pauliuk, S. (2017). Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Life Cycles Using MaTrace-Alloy. *Environ. Sci. Technol.*, *51*, 9469–9476. https://doi.org/10.1021/acs.est.7b01683

Nuss, P., Gian Andrea, B., Willi, H., Andreas, M., Viorel, N., & Pennington, D. (2017). *Development of a Sankey diagram of material flows in the EU economy based on Eurostat. Technical Report*. https://doi.org/10.2760/362116

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*(October 2017), 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Pauliuk, S., Kondo, Y., Nakamura, S., & Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. *Resources, Conservation and Recycling*, *116*, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). *Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions*. https://doi.org/10.1016/j.jclepro.2015.06.100

Schmidt, J. H., Weidema, B. P., & Suh, S. (2010). *Documentation of the final model used for the scenario analyses. FORWAST Deliverable n° 6-4*. https://doi.org/http://forwast.brgm.fr/

Schmidt, J., & Merciai, S. (2017). *Physical/hybrid supply and use tables – methodological report. DESIRE deliverable*. http://fp7desire.eu/documents/category/3-public-deliverables

Schmidt, J., Merciai, S., Delahaye, R., Vuik, J., Heijungs, R., de Koning, A., & Sahoo, A. (2013a). *Recommendation of terminology, classification, framework of waste accounts and MFA, and data collection guideline. CREEA deliverable D4.1*. http://creea.eu/download/public-deliverables

Schmidt, J., Merciai, S., Delahaye, R., Vuik, J., Heijungs, R., de Koning, A., & Sahoo, A. (2013b). *Recommendation of terminology, classification, framework of waste accounts and MFA, and data collection guideline. CREEA deliverable D4.1*.

Stadler, K., Wood, R., Bulavskaya, T., Sodersten, C., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernandez, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2018). EXIOBASE 3. Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, *22*(3), 502–515. https://doi.org/10.1111/jiec.12715

Stanhel, W. R., & Clift, R. (2015). Stocks and Flows in the Peformance Economy. In *Taking Stock of Industrial Ecology* (pp. 137–158). Springer International Publishing. https://doi.org/10.1007/978-3-319-20571-7

Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Suh, S. (2004). A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities. *Ecological Economics*, *48*(1), 9–17. https://doi.org/10.1016/j.ecolecon.2003.09.003

Suh, S., Weidema, B., Schmidt, J. H., & Heijungs, R. (2010). Generalized Make and Use Framework for Allocation in Life Cycle Assessment. *Journal of Industrial Ecology*, *14*(2), 335–353. https://doi.org/10.1111/j.1530-9290.2010.00235.x

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. *Journal of Industrial Ecology*, *00*(0), 1–13. https://doi.org/10.1111/jiec.12562

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2016). Environmental and resource footprints in a global context: Europe’s structural deficit in resource endowments. *Global Environmental Change*, *40*, 171–181. https://doi.org/10.1016/j.gloenvcha.2016.07.002

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J. M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., & Kuenen, J. (2013). Exiopol – Development and Illustrative Analyses of a Detailed Global Mr Ee Sut/Iot. *Economic Systems Research*, *25*(1), 50–70. https://doi.org/10.1080/09535314.2012.761952

Tukker, A., Giljum, S., & Wood, R. (2018). Recent Progress in Assessment of Resource Efficiency and Environmental Impacts Embodied in Trade An Introduction to this Special Issue. *Journal of Industrial Ecology*, *00*(0), 1–13. https://doi.org/10.1111/jiec.12736

van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., & Fellner, J. (2017). Comprehensive analysis and quantification of national plastic flows: The case of Austria. *Resources, Conservation and Recycling*, *117*, 183–194. https://doi.org/10.1016/j.resconrec.2016.10.017

Weisz, H., & Duchin, F. (2006). Physical and monetary input-output analysis: What makes the difference? *Ecological Economics*, *57*(3), 534–541. https://doi.org/10.1016/j.ecolecon.2005.05.011

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.-H., Hubacek, K., & Fischer-

Kowalski, M. (2006). The physical economy of the European Union: Cross-country comparison and determinants of material consumption. *Ecological Economics*, *58*, 676–698. https://doi.org/10.1016/j.ecolecon.2005.08.016

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting : Concepts , Modelling , and Global Application for 1900 – 2050. *Ecological Economics*, *156*, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *PNAS*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825–833. https://doi.org/10.1016/j.rser.2016.09.123

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., & Tukker, A. (2015). Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, *7*(1), 138–163. https://doi.org/10.3390/su7010138

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., & Tukker, A. (2018). Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology*, *22*(3), 553–562. https://doi.org/10.1111/jiec.12735

World-Bank. (2019). *World Bank Country and Lending Groups*.

World-Bank. (2020). *World Bank Open Data*.

Zengwei Yuan, Jun Bi, and Y., & S. (2006). The Circular Economy A New Development Strategy in China. *Journal of Industrial Ecology*, *10*, 4–7. https://doi.org/10.1038/531435a

Zhu, J., Fan, C., Shi, H., & Shi, L. (2018). Efforts for a Circular Economy in China A Comprehensive Review of Policies. *Journal of Industrial Ecology*, *00*(0), 1–9. https://doi.org/10.1111/jiec.12754

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.

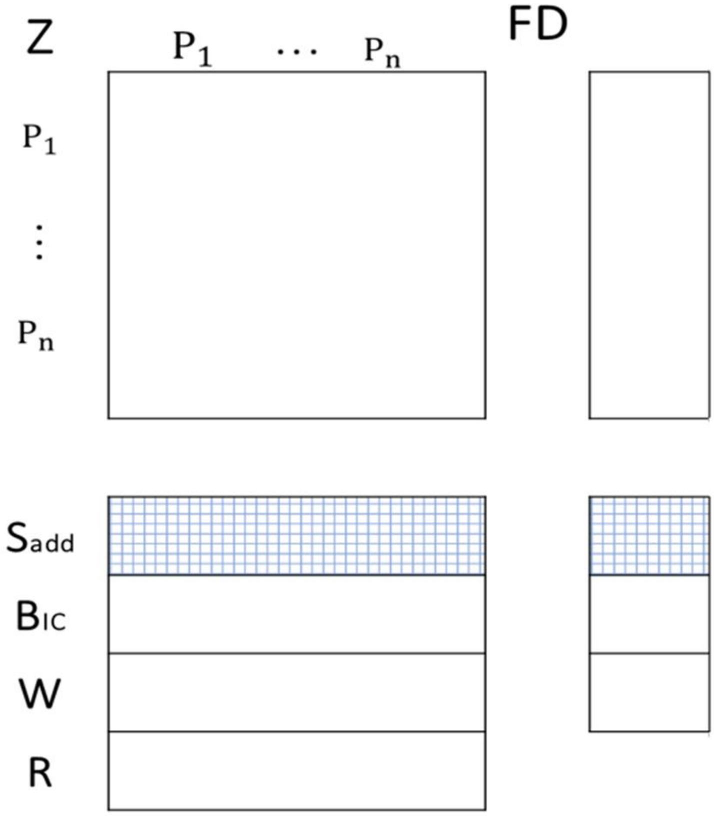

Figure 4.1. Simplified global, multiregional hybrid-units input-output table (MR-HIOT). FD = final demand matrix; Z = intermediate demand matrix; P = product or service; R = resource extraction matrix; W = waste supply and use matrix; B_{IC} = dissipative emission matrix; S_{add} = stock additions matrix. 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. $S_{m,c,t}^{T}$) is equal to the sum of material stock additions in industries ($S_{m,c,t}^{I}$) plus the sum of materials accumulated in final demand ($S_{m,c,t}^{FD}$):

$$S_{m,c,t}^{T} = \sum S_{m,c,t}^{I} + \sum S_{m,c,t}^{FD}. \qquad [4.3]$$

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 ($S_{m,c,t}^{C}$) 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 ($S_{m,c,t}^{V}$), 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 ($S_{m,c,t}^{FD}$ 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 $S_{m,c,t}^{FD}$ from other industries because $S_{m,c,t}^{FD}$ 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 ($S_{m,c,t}^{R}$) 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:

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

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

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).

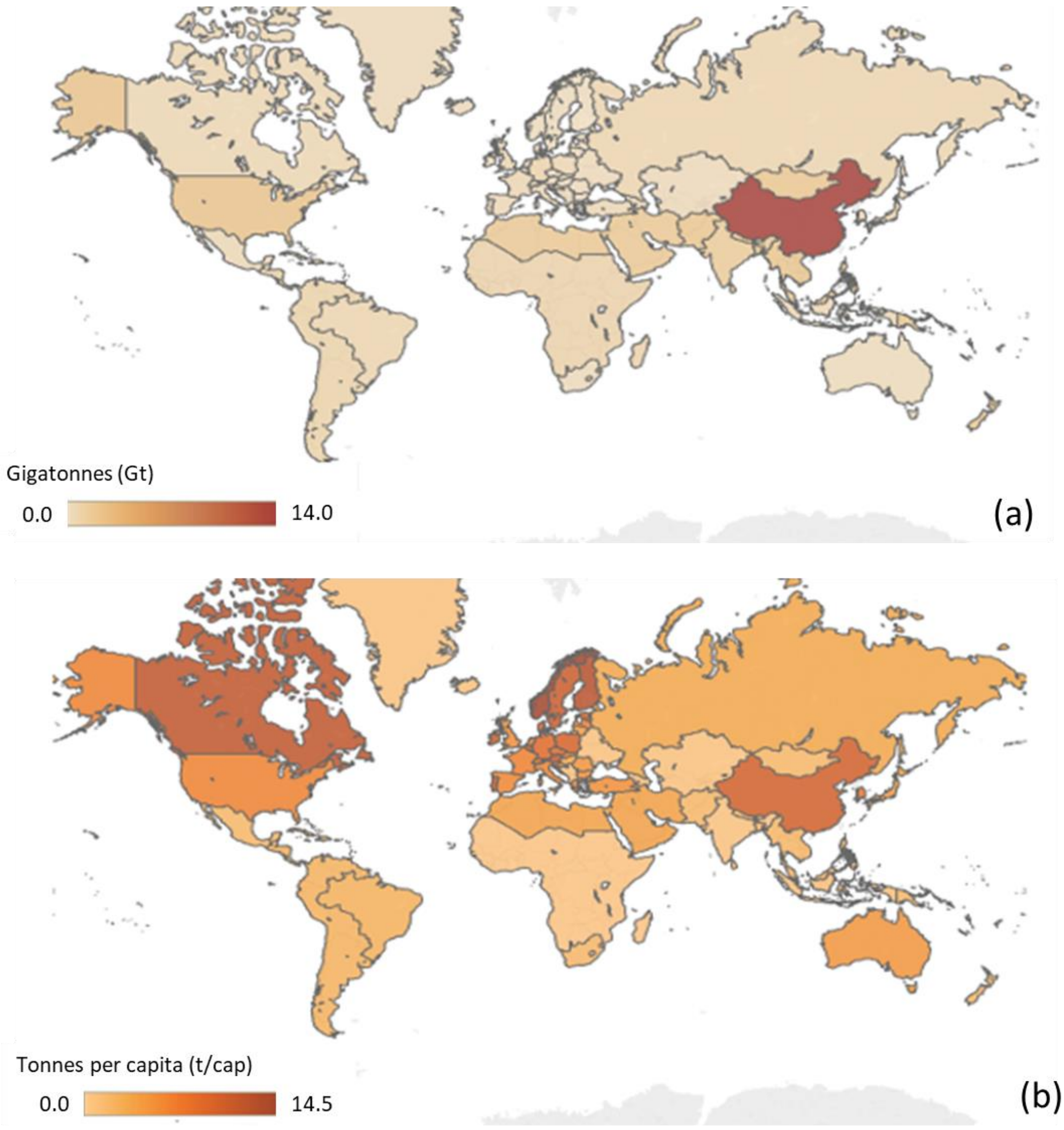

Figure 4.2. Global distribution of material inflows to in-use stocks in (a) absolute values, and (b) per capita for 2011. Total values are in Gigatonnes (Gt), and per capita values are in tonnes per capita (t/cap).

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.

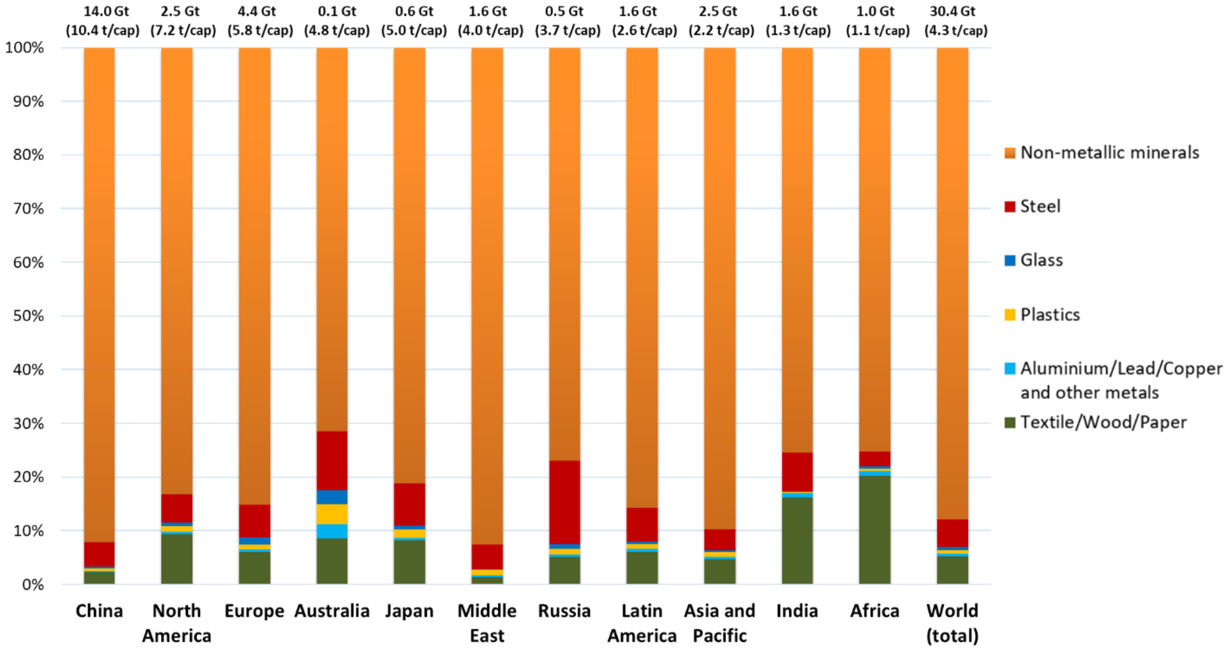

Figure 4.3. Material composition of inflows to in-use stocks for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per capita (t/cap). World (total) represents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

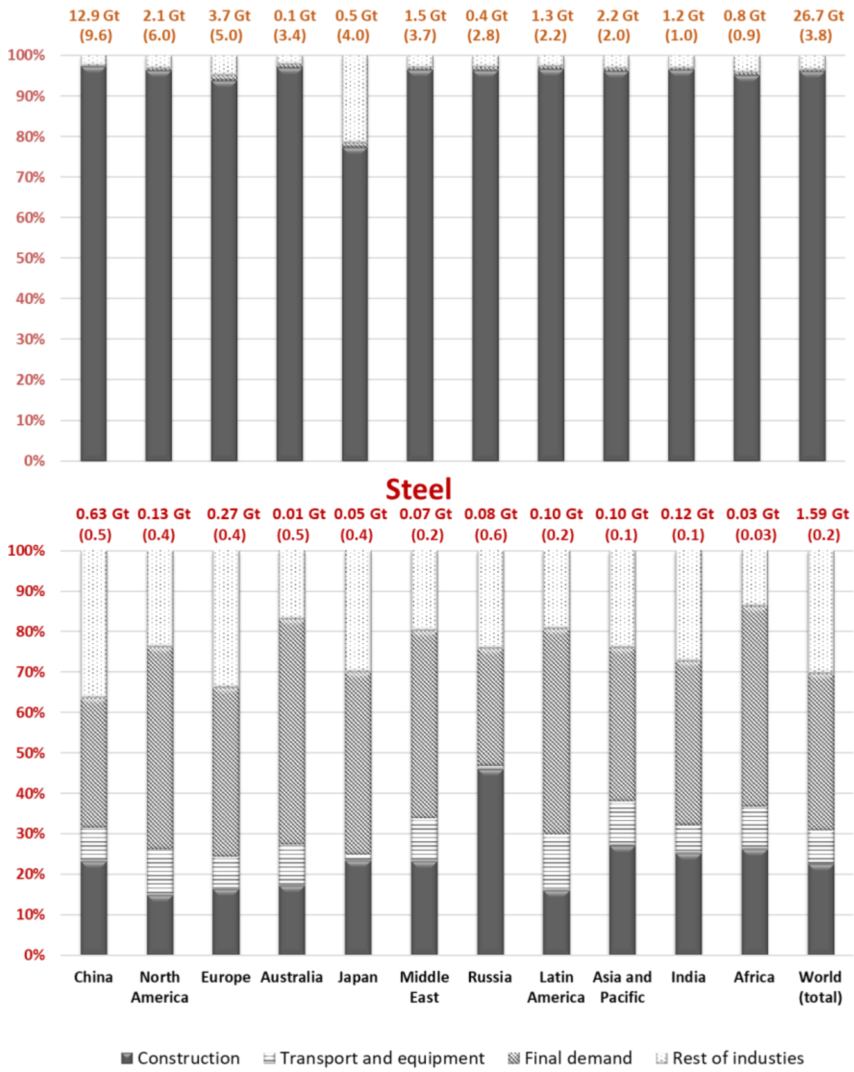

Figure 4.4. Sectoral distribution of inflows to in-use stocks for non-metallic minerals, and steel for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per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

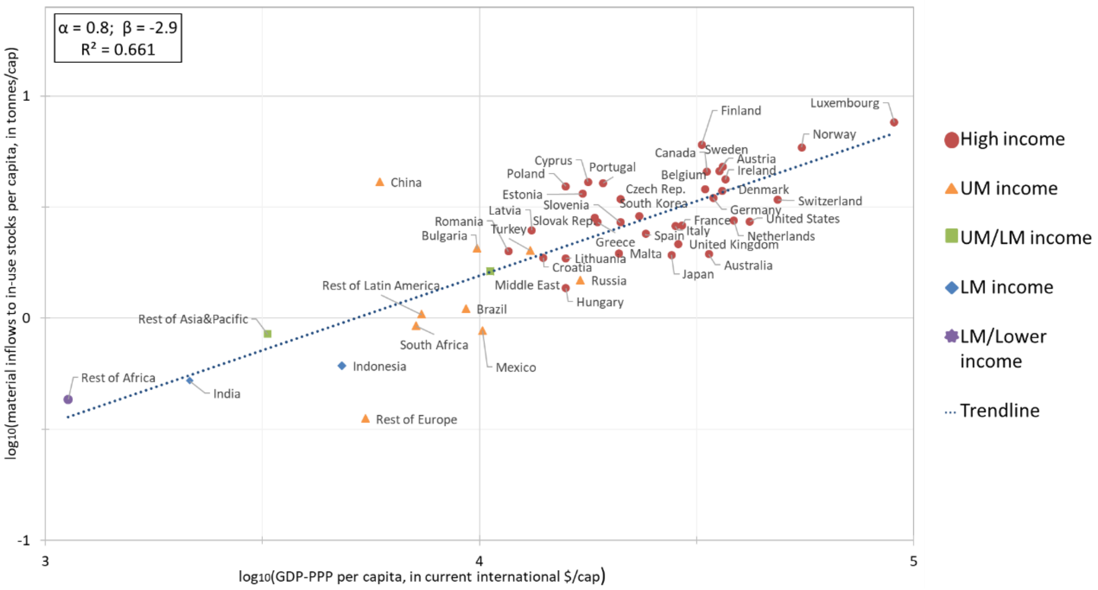

Figure 4.5. Logarithm of material inflows to in-use stocks (in tonnes/cap) over logarithm of gross domestic product, purchasing power parity per capita (GDP-PPP/cap), in current international $/cap). Red circles denote high income countries. Orange triangles indicate upper middle income (UM) countries. 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.

4.5. References

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Merciai, S., Schmidt, J., Rodrigues, J. F. D., & Tukker, A. (2019). The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011. *Resources, Conservation and Recycling*, *151*. https://doi.org/10.1016/j.resconrec.2019.104452

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions : a review of EEIOA-based studies. *Journal of Economic Structures*, *7*(14), 1–24. https://doi.org/10.1186/s40008-018-0113-3

Beylot, A., & Villeneuve, J. (2015). Assessing the national economic importance of metals: An Input-Output approach to the case of copper in France. *Resources Policy*, *44*, 161–165. https://doi.org/10.1016/j.resourpol.2015.02.007

Bleischwitz, R., Nechifor, V., Winning, M., Huang, B., & Geng, Y. (2018). Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling. *Global Environmental Change*, *48*(October 2017), 86–96. https://doi.org/10.1016/j.gloenvcha.2017.11.008

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*. https://doi.org/10.1016/j.resconrec.2019.104508

Dong, D., Tukker, A., & Van der Voet, E. (2019). Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *Journal of Industrial Ecology*, *23*(6), 1363–1380. https://doi.org/10.1111/jiec.12926

EC. (2001). *Economy-wide material flow accounts and derived indicators. Technical Report*.

Ellen MacArthur Foundation. (2015). Growth within: a circular economy vision for a competitive Europe. In *Ellen MacArthur Foundation*. https://doi.org/Article

Eurostat. (2013). *Economy-wide Material Flow Accounts (EW-MFA) Compilation Guide 2013* (Issue July). http://ec.europa.eu/eurostat/web/environment/methodology

Fishman, T., Schandl, H., & Tanikawa, H. (2016). Stochastic Analysis and Forecasts of the Patterns of Speed, Acceleration, and Levels of Material Stock Accumulation in Society. *Environmental Science and Technology*, *50*(7), 3729–3737. https://doi.org/10.1021/acs.est.5b05790

Gorman, M., & Dzombak, D. (2020). Stocks and flows of copper in the U.S.: Analysis of circularity 1970–2015 and potential for increased recovery. *Resources, Conservation and*

Recycling, *153*(August 2019), 104542. https://doi.org/10.1016/j.resconrec.2019.104542
Graedel, T. E. (2019). Material Flow Analysis from Origin to Evolution. *Environmental Science and Technology*, *53*(21), 12188–12196. https://doi.org/10.1021/acs.est.9b03413
Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/jiec.12244
Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020). Spaceship earth's odyssey to a circular economy - a century long perspective. *Resources, Conservation and Recycling*, *163*(August), 105076. https://doi.org/10.1016/j.resconrec.2020.105076
Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., & Creutzig, F. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: Synthesizing the insights. *Environmental Research Letters*, *15*(6). https://doi.org/10.1088/1748-9326/ab842a
Hoekstra, R., & van den Bergh, J. C. J. M. (2006). Constructing physical input-output tables for environmental modeling and accounting: Framework and illustrations. *Ecological Economics*, *59*(3), 375–393. https://doi.org/10.1016/j.ecolecon.2005.11.005
IRP. (2019). *Global Resource Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel*. https://www.resourcepanel.org/reports/global-resources-outlook
IRP. (2020). *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. A report of the International Resource Panel*. https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change
Jacobi, N., Haas, W., Wiedenhofer, D., & Mayer, A. (2018). Providing an economy-wide monitoring framework for the circular economy in Austria : Status quo and challenges. *Resources, Conservation & Recycling*, *137*, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022
Jiang, M., Behrens, P., Wang, T., Tang, Z., Yu, Y., Chen, D., Liu, L., Ren, Z., Zhou, W., Zhu, S., He, C., Tukker, A., & Zhu, B. (2019). Provincial and sector-level material footprints in China. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(52), 26484–26490. https://doi.org/10.1073/pnas.1903028116
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K. H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics*, *68*(10), 2696–2705. https://doi.org/10.1016/j.ecolecon.2009.05.007
Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to out fl ows of wastes and emissions : The socioeconomic metabolism of the global economy , 1900 – 2015. *Global Environmental Change*, *52*, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003
Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., & Fishman, T. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS*, *114*(8), 21–26. https://doi.org/10.1073/pnas.1613773114
Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking Stock of Built Environment Stock Studies: Progress and Prospects. *Environmental Science and Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652
Lenzen, M., Wood, R., & Wiedmann, T. (2010). Uncertainty analysis for multi-region input -

output models - a case study of the UK'S carbon footprint. *Economic Systems Research*, *22*(1), 43–63. https://doi.org/10.1080/09535311003661226
Marinova, S., Deetman, S., van der Voet, E., & Daioglou, V. (2020). Global construction materials database and stock analysis of residential buildings between 1970-2050. *Journal of Cleaner Production*, *247*, 119146. https://doi.org/10.1016/j.jclepro.2019.119146
Mayer, A., Haas, W., Wiedenhofer, D., Nuss, P., & Blengini, G. A. (2018). Measuring Progress towards a Circular Economy A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, *00*(0), 1–15. https://doi.org/10.1111/jiec.12809
McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., & Doménech, T. (2017). Circular Economy Policies in China and Europe. *Journal of Industrial Ecology*, *21*(3), 651–661. https://doi.org/10.1111/jiec.12597
Merciai, S, Schmidt, J. H., Dalgaard, R., Giljum, S., Lutter, S., Usubiaga, A., Acosta, J., Schütz, H., Wittmer, D., & Delahaye, R. (2014). *Report and data Task 4.2: P-SUT. Deliverable 4-2 of the EU FP7-project CREEA.* http://creea.eu/index.php/documents2/cat_view/9-public-deliverables
Merciai, Stefano, & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *00*(0), 1–16. https://doi.org/10.1111/jiec.12713
Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., & Tanikawa, H. (2017). Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, *127*, 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024
Müller, D. B., Wang, T., & Duval, B. (2011). Patterns of iron use in societal evolution. *Environmental Science and Technology*, *45*(1), 182–188. https://doi.org/10.1021/es102273t
Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., & Pauliuk, S. (2017). Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Life Cycles Using MaTrace-Alloy. *Environ. Sci. Technol.*, *51*, 9469–9476. https://doi.org/10.1021/acs.est.7b01683
OECD. (2008). *Measuring Material Flows and Resource Productivity: Vol. I*. http://www.oecd.org/dataoecd/46/48/40485853.pdf%5Cnpapers2://publication/uuid/686D0BB7-44D3-454F-8D23-02FE7A24E1E8
Owen, A., Steen-Olsen, K., Barrett, J., Wiedmann, T., & Lenzen, M. (2014). A Structural Decomposition Approach To Comparing MRIO Databases. *Economic Systems Research*, *26*(3), 262–283. https://doi.org/10.1080/09535314.2014.935299
PANORAMA. (2020). *Building a comprehensive Supply Chain Database*. https://cml.liacs.nl/panorama/about/
Pauliuk, S. (2020). *Documentation of part IV of the RECC model framework: Open Dynamic Material Systems Model for the Resource Efficiency-Climate Change Nexus (ODYM-RECC), v2.2*. https://doi.org/https://doi.org/10.31235/osf.io/y4xcv
Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change*, *7*(1), 13–20. https://doi.org/10.1038/nclimate3148
Pauliuk, S., Kondo, Y., Nakamura, S., & Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. *Resources, Conservation and Recycling*, *116*, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029
Pauliuk, S., & Müller, D. B. (2014). The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change*, *24*(1), 132–142.

https://doi.org/10.1016/j.gloenvcha.2013.11.006
Pauliuk, S., Wang, T., & Daniel, B. M. (2012). Moving Toward the Circular Economy : The Role of Stocks in the Chinese Steel Cycle. *Environ. Sci. Technol*, *46*, 148–154. https://doi.org/10.1021/es201904c
Pauliuk, S., Wood, R., & Hertwich, E. G. (2015). Dynamic Models of Fixed Capital Stocks and Their Application in Industrial Ecology. *Journal of Industrial Ecology*, *19*(1), 104–116. https://doi.org/10.1111/jiec.12149
Pfaff, M., Glöser-Chahoud, S., Chrubasik, L., & Walz, R. (2018). Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures. *Resources, Conservation and Recycling*, *139*, 205–218. https://doi.org/10.1016/j.resconrec.2018.08.017
Schaffartzik, A., Duro, J. A., & Krausmann, F. (2019). Global appropriation of resources causes high international material inequality – Growth is not the solution. *Ecological Economics*, *163*(August 2018), 9–19. https://doi.org/10.1016/j.ecolecon.2019.05.008
Schiller, G., Müller, F., & Ortlepp, R. (2017). Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resources, Conservation and Recycling*, *123*, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007
Schmidt, J., & Merciai, S. (2017). *Physical/hybrid supply and use tables – methodological report. DESIRE deliverable*. http://fp7desire.eu/documents/category/3-public-deliverables
Sigüenza, C. P., Steubing, B., Tukker, A., & Aguilar-Hernández, G. A. (2020). The environmental and material implications of circular transitions: A diffusion and product-life-cycle-based modeling framework. *Journal of Industrial Ecology*, 1–17. https://doi.org/10.1111/jiec.13072
Södersten, C. J., Wood, R., & Hertwich, E. G. (2018a). Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting. *Environmental Science and Technology*, *52*(22), 13250–13259. https://doi.org/10.1021/acs.est.8b02791
Södersten, C. J., Wood, R., & Hertwich, E. G. (2018b). Environmental Impacts of Capital Formation. *Journal of Industrial Ecology*, *22*(1), 55–67. https://doi.org/10.1111/jiec.12532
Södersten, C. J., Wood, R., & Wiedmann, T. (2020). The capital load of global material footprints. *Resources, Conservation and Recycling*, *158*, 104811. https://doi.org/10.1016/j.resconrec.2020.104811
Song, L., Wang, P., Xiang, K., & Chen, W. Q. (2020). Regional disparities in decoupling economic growth and steel stocks: Forty years of provincial evidence in China. *Journal of Environmental Management*, *271*, 111035. https://doi.org/10.1016/j.jenvman.2020.111035
Soulier, M., Pfaff, M., Goldmann, D., Walz, R., Geng, Y., Zhang, L., & Tercero Espinoza, L. A. (2018). The Chinese copper cycle: Tracing copper through the economy with dynamic substance flow and input-output analysis. *Journal of Cleaner Production*, *195*, 435–447. https://doi.org/10.1016/j.jclepro.2018.04.243
Stahel, W. R., & Clift, R. (2015). Stocks and Flows in the Peformance Economy. In *Taking Stock of Industrial Ecology* (pp. 137–158). Springer International Publishing. https://doi.org/10.1007/978-3-319-20571-7
Steinberger, J. K., Krausmann, F., & Eisenmenger, N. (2010). Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics*, *69*(5), 1148–1158. https://doi.org/10.1016/j.ecolecon.2009.12.009
Suh, S. (2004). A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities. *Ecological Economics*, *48*(1), 9–17. https://doi.org/10.1016/j.ecolecon.2003.09.003

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. *Journal of Industrial Ecology*, *00*(0), 1–13. https://doi.org/10.1111/jiec.12562

Towa, E., Zeller, V., & Achten, W. M. J. (2020). Input-output models and waste management analysis: A critical review. *Journal of Cleaner Production*, *249*, 119359. https://doi.org/10.1016/J.JCLEPRO.2019.119359

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2014). *The Global Resource Footprint of Nations: Carbon, water, land and materials embodied in trade and final consumption*.

Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., & Wood, R. (2016). Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environmental Change*, *40*, 171–181. https://doi.org/10.1016/j.gloenvcha.2016.07.002

UN. (2009). System of National Accounts. In *Non-Extensive Entropy Econometrics for Low Frequency Series*.

UNEP. (2019). *Emissions Gap Report 2019*.

Weisz, H., & Duchin, F. (2006). Physical and monetary input-output analysis: What makes the difference? *Ecological Economics*, *57*(3), 534–541. https://doi.org/10.1016/j.ecolecon.2005.05.011

Wiebe, K. S., Bjelle, E. L., Többen, J., & Wood, R. (2018). Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. *Journal of Economic Structures*, *7*(1). https://doi.org/10.1186/s40008-018-0118-y

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting : Concepts , Modelling , and Global Application for 1900 – 2050. *Ecological Economics*, *156*, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *PNAS*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

World-Bank. (2019). *World Bank Country and Lending Groups*.

World-Bank. (2020). *World Bank Open Data*.

Wuyts, W., Miatto, A., Sedlitzky, R., & Tanikawa, H. (2019). Extending or ending the life of residential buildings in Japan: A social circular economy approach to the problem of short-lived constructions. *Journal of Cleaner Production*, *231*, 660–670. https://doi.org/10.1016/j.jclepro.2019.05.258

Zeng, X., Zheng, H., Gong, R., Eheliyagoda, D., & Zeng, X. (2018). Uncovering the evolution of substance flow analysis of nickel in China. *Resources, Conservation and Recycling*, *135*, 210–215. https://doi.org/10.1016/j.resconrec.2017.10.014

Chapter 5

Macroeconomic, social, and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies

Based on: Aguilar-Hernandez, G.A., J.F.D. Rodrigues, and A. Tukker. (2020). Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. *Journal of Cleaner Production.* https://doi.org/10.1016/j.jclepro.2020.123421

Abstract

The potential impacts on gross domestic product, employment, and carbon emissions of implementing a circular economy have been modelled at the national and multiregional levels using multiple scenarios. However, there is still no consensus on the magnitude of the impacts of a transition to a circular economy and on whether it will generate a 'win-win-win' situation in terms of macroeconomic, social and environmental benefits. In this chapter, we review more than 300 circular economy scenarios in the time frame from 2020 to 2050. We classify each scenario according to the degree of intervention (i.e. ambitious or moderate), and perform a meta-analysis of the changes in gross domestic product, job creation, and CO_2 emissions generated by each circular economy scenario compared with a business-as-usual scenario. Among other results, we find that in 2030 the implementation of ambitious circular economy scenarios could generate a 'win-win-win' situation with marginal or incremental changes in gross domestic product (median (mdn) = 2.0%; interquartile range (IQR) = [0.4–4.6]%) and employment (mdn = 1.6%; IQR = [0.9–2.0]%), while reducing CO_2 emissions in a more substantial way (mdn = -24.6%; IQR = -[34.0–8.2]%). Furthermore, we discuss the modelling features (e.g. resource taxes, technology changes, and consumption patterns) suggested in the literature which yield the greatest changes in gross domestic product, job creation, and CO_2 emissions. The outcomes of this chapter are relevant to the scientific community and policy makers for understanding the magnitude of the macroeconomic, social and environmental impacts of circular economy scenarios.

Keywords: circular economy, resource efficiency, computable general equilibrium, input-output analysis, scenario analysis

5.1. Introduction

Society currently faces the challenges of satisfying human needs and preserving biological diversity and resources as well as tackling climate change (de Coninck et al., 2018). These aspects have been considered in the sustainability field, which integrates economic, social and environmental dimensions (Bonan & Doney, 2018; Valdivia et al., 2013). In the context of sustainability policies, resource efficiency has been proposed as a key measure to reach prosperity (Allwood et al., 2010; IRP, 2019). In particular, the circular economy is recognized as a paradigm that enables changes in global resource management and contributes to achieving sustainability (Ghisellini et al., 2016; WEF, 2014).

Several literature reviews have been carried out in the field of circular economy. Most researchers have focused on the concept of circular economy and its implementation in business models and new technologies (see, for example, Geissdoerfer et al., 2017; Kirchherr et al., 2017; Pan et al., 2015; Tukker, 2015). Nevertheless, as shown in Chapter 2, there is still little understanding of the magnitude of potential socio-economic and environmental impacts of a transition to a circular economy at the macro level, i.e. on national, multinational and global scales (Wiebe et al., 2019; Woltjer, 2018). The macro-level perspective is essential for identifying which policy measures can be implemented to promote a cost-effective circularity transition (Geng et al., 2012a; McDowall et al., 2017). Due to the dearth of literature on the macro-level implications of a transition to a circular economy, our study is specifically focused on the macro-level perspective of circularity.

Moreover, multiple measures that enhance resource use and retain materials inside the economy - here, circularity interventions - have been proposed by McDowell et al. (2017) and the Ellen MacArthur Foundation (EMF, 2013). As described in Chapter 2, circularity interventions can be grouped into four types: closing supply chains, residual waste management, product lifetime extension, and resource efficiency (Aguilar-Hernandez et al., 2018). Currently, governments are increasingly interested in monitoring the performance of circularity interventions (Geng et al., 2012; Linder et al., 2017; Mayer et al., 2018). This has led to the emergence of a plethora of studies that try to understand what the impacts of a widespread adoption of circularity interventions (i.e. a circularity transition) will be. To do so requires elaborating circular economy scenarios (CESs), i.e., consistent and coherent descriptions of possible future developments if circularity interventions were implemented (van Notten, 2006; Woltjer, 2018). Several previous publications, which we survey in the following paragraphs, report critical reviews of CESs. The reason for reviewing these publications is that they revised CESs at country and global scales.

McCarthy et al. (2018) surveyed journal articles and grey literature on the macroeconomic assessment of a circular economy. The authors provided an overview of the methods used to analyze the effects of circular economy policies. They focused on studies using macroeconomic models, such as the computable general equilibrium model (CGE) and CGE-based models (see, for example, Cambridge Econometrics, European Commission, 2014; Winning et al., 2017). Furthermore, they assessed the macroeconomic models in 4 dimensions: geography, sectors, material coverage, and economic instruments. Most of the models reviewed by McCarthy et al. (2018) reported CESs which by 2030 contribute to changes of 0 to 15% in gross domestic product (GDP) compared to a baseline scenario. The researchers also discussed how modelling circularity interventions could involve a shift in material extraction and material use across different countries. The authors also highlighted the importance of model assumptions regarding the level of productivity growth, the quantity and quality of materials, and consumption patterns for the magnitude of the model outcomes.

Best et al. (2018) examined the literature on the potential effects of circularity interventions in the European Union (EU). The authors summarized the studies regarding material efficiency and CES. Furthermore, they provided quantitative evidence of GDP and employment changes based on the scenario analysis. The numerical values reported in that study were retrieved from the Circular Impacts Project (CI, 2018), which provides a comprehensive and publicly available online library of circular economy studies. Their findings showed that CESs ranged from -6% to 7% of GDP, and from -0.1% to 1% of job creation compared to baseline scenario in 2030. Best et al. (2018) also suggested that the wide range of macroeconomic indicators is caused by the assumptions used in each model, which include rebound effects, technological changes, recycling feasibility, consumer behavior, and trade-offs between countries.

Besides the macroeconomic and integrated assessment models reviewed above, some studies also used structural models to assess the impact of CESs. Structural models use the connections between economic sectors and final demand to estimate the socioeconomic and environmental impacts of consumption (de Koning, 2018; Donati et al., 2020). A particular type of structural models uses environmentally extended input–output analysis (EEIOA), and several EEIOA-based models have explored the socioeconomic and environmental impacts of CESs at national and multi-regional levels.

Even though the reviews mentioned above compiled extensive literature on CESs and their potential impacts, the researchers did not statistically analyze the socioeconomic and environmental impacts of the CESs surveyed. Furthermore, to the best of our knowledge, no published study has examined the interactions between the impacts of circularity interventions across different indicators, i.e., whether there are trade-offs between macroeconomic, social or environmental impacts. We aim to fill this research gap by performing a statistical analysis of CES literature that correlates macroeconomic, social and environmental indicators in order to determine if circularity interventions could result in a ‘win-win-win’ situation at the macro scale.

In this chapter, we perform a meta-analysis of CESs from 2020 to 2050, assessing changes in GDP, employment, and CO_2 emissions at the macro scale. Our aims are to examine whether there is a consensus among existing prospective studies and to statistically quantify the changes in each indicator (GDP, employment, CO_2 emissions) compared to a baseline scenario, which will be explained in section 2. We then combine the three indicators and perform a correlation analysis between these indicators to determine whether a circularity transition could lead to a ‘win-win-win’ situation in terms of macroeconomic, social and environmental impacts. Finally, we discuss the modelling features (i.e. the specific attributes or aspects modelled in each CES, such as resource taxes, technology changes, etc.) that yield the major changes in GDP, employment, and CO_2 emissions suggested by the literature. This chapter presents a novel approach to harmonizing values across CESs from multiple publications, and to performing a meta-analysis in a consistent framework. Our findings are relevant to the scientific community and policy makers, as these results provide insight into the magnitude of the macroeconomic, social, and environmental impacts of CESs.

The chapter proceeds as follows: Section 5.2 presents methods and data, including literature search, eligibility criteria and meta-analysis; Section 5.3 shows the outcomes of the literature review and meta-analysis; Section 5.4 discusses the findings in the context of the key measures proposed in the literature to promote a circularity transition, the modelling limitations and suggestions for further research; Section 5.5 presents the final conclusions.

5.2. Method and data

The following section is divided into two parts: literature search and eligibility criteria, and meta-analysis. First, we explain the literature search and eligibility criteria, including the steps in which publications were retrieved from search engines as well as the reasons for including or excluding certain records (i.e. specific scientific journal papers or technical reports that are publications from grey literature). Second, we describe the steps of the meta-analysis, which includes collecting data from selected publications, harmonizing their values, and performing a correlation analysis.

5.2.1. Literature search and eligibility criteria

We conducted a literature search on December 2019 following the PRISMA guidelines for reporting a transparent systematic review and meta-analysis (Moher et al., 2015). The PRISMA guidelines have been widely applied to meta-analyses in medicine and other fields for developing systematic reviews and meta-analyses in a consistent way (Liberati et al., 2009; Zumsteg et al., 2012), thus providing a suitable framework for our own literature search. Although several studies report other approaches for performing literature reviews and meta-analysis (Horváthová, 2010, for example, 2012; Luederitz et al., 2016), the PRISMA guidelines provide a suitable framework to perform systematic reviews and meta-analysis in a transparent way, and their application in sustainability studies has increased in recent years (see, for example, Blanco et al., 2020; Jin et al., 2019; van Zalk & Behrens, 2018).

The three indicators assessed in this chapter were GDP, employment (or job creation), and CO_2 emissions. These indicators can be used to represent the macroeconomic, social and environmental impacts, which are three main dimensions considered in the sustainability field (Valdivia et al., 2013). Assessing the impacts of CESs on these indicators is essential to evaluate the implementation of circular economy policies (McDowall et al., 2017).

We used the web search engines Web of Science, Circular Impact Project Library (CI, 2018), and Google Scholar to retrieve peer-reviewed and grey literature in English without restrictions on the time period. We searched for terms describing 'circular economy' combined with macro-indicators terms, such as 'GDP' OR 'job creation' OR 'employment' OR 'carbon emission' OR 'CO2' (see worksheet figure_1 in file data_source.xlsx of Supplementary Material for a detailed list of key words used in each search engine). We also completed these searches with the snowballing procedure described by Wolhin (2014). The expected result of this step is that we collect the CES literature in a systematic way.

The search resulted in the retrieval of 595 publications (see figure 5.1), which were eligible for the meta-analysis if the studies met all of the following 4 criteria:

At least one circularity intervention type (i.e. closing supply chain, product lifetime extension, residual waste management, or resource efficiency based on Aguilar-Hernandez et al. (2018)) was assessed;

At least one macroeconomic, social or environmental indicator – here, GDP, job creation and CO_2 emissions, respectively - was quantified as a model outcome;

The impacts at national, multi-national or global scales were assessed with structural, macro-economic or integrated assessment models (as described by de Koning (2018));

And prospective scenarios were analyzed from 2020 to 2050 in comparison with a respective baseline scenario.

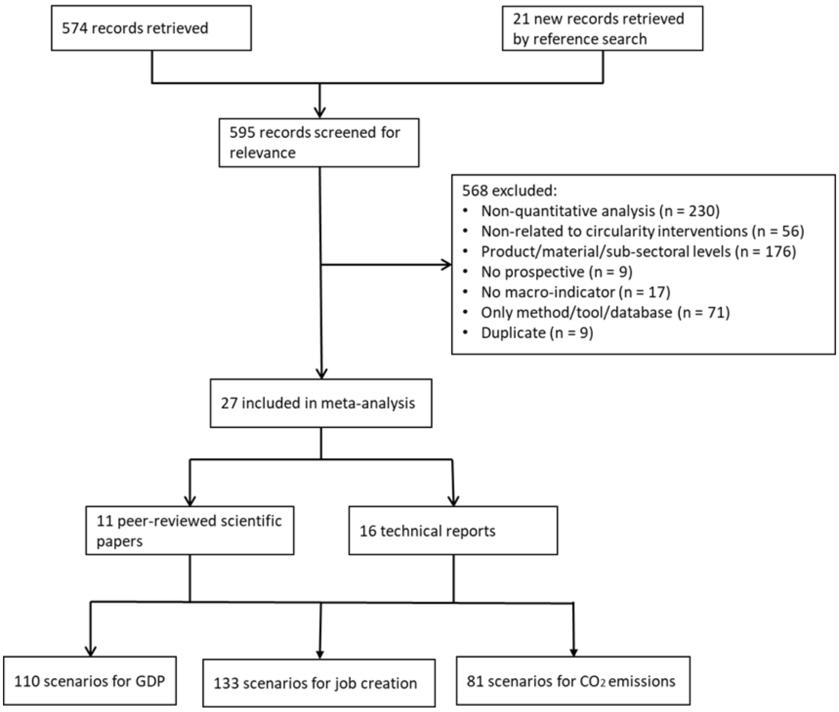

Figure 5.1. Flowchart of the inclusion of selected publications (status in December, 2019). A record is a scientific journal paper and/or technical report (i.e. publication from grey literature). Retrieved records are the publications that were found using the search engines. Excluded records are the publications that did not meet the eligibility criteria and were discarded from the meta-analysis.

The literature search resulted in 27 relevant papers, which accounted for 324 CESs (see table 1). Of the 27 studies, 6 (22% of the total) estimated only CO_2 emissions, 3 (11%) estimated job creation, 1 (4%) estimated GDP, and 17 (63%) combined the three indicators. The geographical dimension consisted of 8 (30%) studies focused on the national level, 9 (33%) related to a multi-regional level, and 11 (37%) that combined national, multi-national and global scales. Regarding the circularity intervention types, 8 publications (30%) assessed resource efficiency, 3 (11%) assessed closing supply chains, 1 (4%) assessed residual waste management only, and 15 (55%) integrated product lifetime extension, closing supply chains, residual waste management and resource efficiency.

The exclusion of almost 95% of records was due to the fact that these publications did not meet the eligibility criteria mentioned above. They were excluded for not being quantitative assessments of CESs (40% of all excluded records); for not being a macro-level assessment but focusing on product, material, or sectoral scales (31%); for lacking at least one of the 4 circularity interventions (10%); for lacking at least one of the three macro-level indicators (3%); for lacking any estimation and instead only showing methods, tools, or databases (12%); for not being prospective CESs from 2020 to 2050 (2%); and for being duplicates retrieved from different search engines (2%).

We extracted the numerical values directly from tables and text in the selected documents, or from figures by using the WebPlotDigitalizer version 4.2 (Rohatgi, 2019). We also collected information about historical data and input parameters for each study (e.g. changes of recycling market shares, technological market penetration, investment levels, taxation rates, and price elasticities). Further information on the selected literature is available in worksheet selected_literature in the file data_source.xlsx of the Supplementary Materials.

Table 5.1. Overview of models used by the selected 27 publications

Type*	**Number of studies**	**Model name abbreviation****	**References**
Macro-economic models	17	ICES/MEMO/MEWA	Bosello et al. (2016)
		E3ME	Cambridge Econometrics (CE, 2018; European Commission, 2014)
		PANTA RHEI	Distelkamp et al. (2010)
		EXIOMOD/LPJmL	Hu et al. (2015)
		GINFORS/LPJmL	Meyer et al. (2015)
		GINFORS3	Meyer et al. (2018)
		GTAP	Lee (2018)
		NewERA	Tuladhar et al. (2016)
		GTEM, GLOBIOM	UNEP (UNEP, 2017)
		ENGAGE-material	Winning et al. (2017)
		Miscellaneous	Böhringer and Rutherford (2015)
			Ellen MacArthur Foundation (EMF, 2015)
			Ellen MacArthur Foundation and McKinsey Center (Ellen MacArthur Foundation, 2015)
			Hatfield-Dodds et al. (2017)
			Rademaekers et al. (2017)
			Groothuis (2016)
Structural models	9	EMEC/NatWaste/SWEA	Söderman et al. (2016)
		Miscellaneous	Beasley and Georgeson (2014)
			Beccarello and Di Foggia (2018)
			European Environmental Agency (EEA, 2014)
			Mitchell and Doherty (2015)
			Morgan and Mitchell (2015)
			Wiebe et al. (Wiebe et al., 2019)
			Wijkman and Skånberg (2015)
			Xuan and Yue (2017)
Integrated assessment models	1	GIAM	Schandl et al. (Schandl et al., 2016)

*Model types are categorized according to the de Koning (2018) classification

**A list of model names is provided in table_1 spreadsheet, data_source.xlxs file in supplementary information

5.2.2. Meta-analysis

We performed a meta-analysis following 3 steps: 1) we extracted the numerical values of CESs and normalized them in order to compare them between different studies, 2) we classified the CESs into categories we ourselves defined as ambitious or moderate scenarios, and 3) we performed statistical analyses including an assessment of correlation between the indicators.

In this study, CESs are consistent and coherent descriptions of possible future impacts if circularity interventions were implemented (van Notten, 2006; Woltjer, 2018). In other words, CESs are exploratory scenarios of 'what-if' a circularity transition was put into action. The impacts of such a transition are expressed by specific numerical values of the macroeconomic, social, and environmental impacts retrieved from each model. We focus on CESs that contain numerical values of GDP, job creation and CO_2 emissions compared to a business-as-usual (BAU) scenario in the time frame from 2020 to 2050. Notice that the impacts are yielded in a particular year. In the beginning we have over 300 CESs in total across different years and studies, which will be combined as described below.

We harmonized the values across the studies by normalizing each CES with respect to a BAU scenario reported by each publication. BAU scenarios were calibrated in each publication by considering the trend of GDP, population growth, and energy and material consumption based on projections from the United Nations Statistics Division, the International Energy Agency, Eurostat, or national statistical offices (Groothuis, 2016; UNEP, 2017; Wiebe et al., 2019). We estimated the difference between a CES and a BAU scenario as follows:

$$\Delta CES_{i,t} = \frac{CES_{i,t} - BAU_{i,t}}{BAU_{i,t}} \times 100, \qquad [5.1]$$

where $\Delta CES_{i,t}$ represents the changes in indicator i (i.e. GDP, job creation, or CO_2 emissions) for year t (from 2020 to 2050), $CES_{i,t}$ and $BAU_{i,t}$ denote the absolute value of the circular economy scenario and the business-as-usual scenario for i in t, respectively. We used $\Delta CES_{i,t}$ as an indicator to compare the macroeconomic, social, and environmental impacts of circularity interventions across the literature.

As an example of the normalization procedure, the study of the Ellen MacArthur Foundation and McKinsey Center (2015) showed two GDP scenarios for the European Union in 2030: 104 billion euros for BAU, and 111 billion euros for CESs. Following equation 1, we normalized these values and calculated a change in GDP of 6.7% (i.e.$\Delta CES_{GDP,2030} = [(111 - 104)/104] \times 100$).

We classified the CESs into two categories: moderate or ambitious. Previous studies on the assessment of policy scenarios showed that classifying scenarios as BAU, moderate and ambitious is a suitable system for comparing and connecting groups of multiple scenarios (Best et al., 2018; Wang et al., 2019). If a study reported more than two scenarios, we classified those as ambitious scenarios that presented the largest impact on GDP, job creation, or CO_2 emissions compared to the BAU scenario. All other scenarios reported in a study besides the BAU and the ambitious scenarios are considered moderate. For studies that only contain one CES, we categorized the scenarios based on the number of economic sectors covered by the CES. We considered a CES ambitious if circularity interventions were implemented in two or more economic activities simultaneously, and moderate if the interventions were applied to only one economic sector.

A single study always has one ambitious scenario and can have either zero, one or multiple moderate scenarios per country or region. To assign equal weight to each study, all moderate scenarios within each study were combined into a single moderate 'study' scenario by calculating the arithmetic average of all moderate scenarios. Furthermore, countries and regions within each study were combined into a single average per scenario type. Thus, in the final analysis we considered 27 studies, with one ambitious scenario and at the most one average moderate scenario each. Figure 5.2 shows an example of data harmonization using the CESs reported by UNEP (2017).

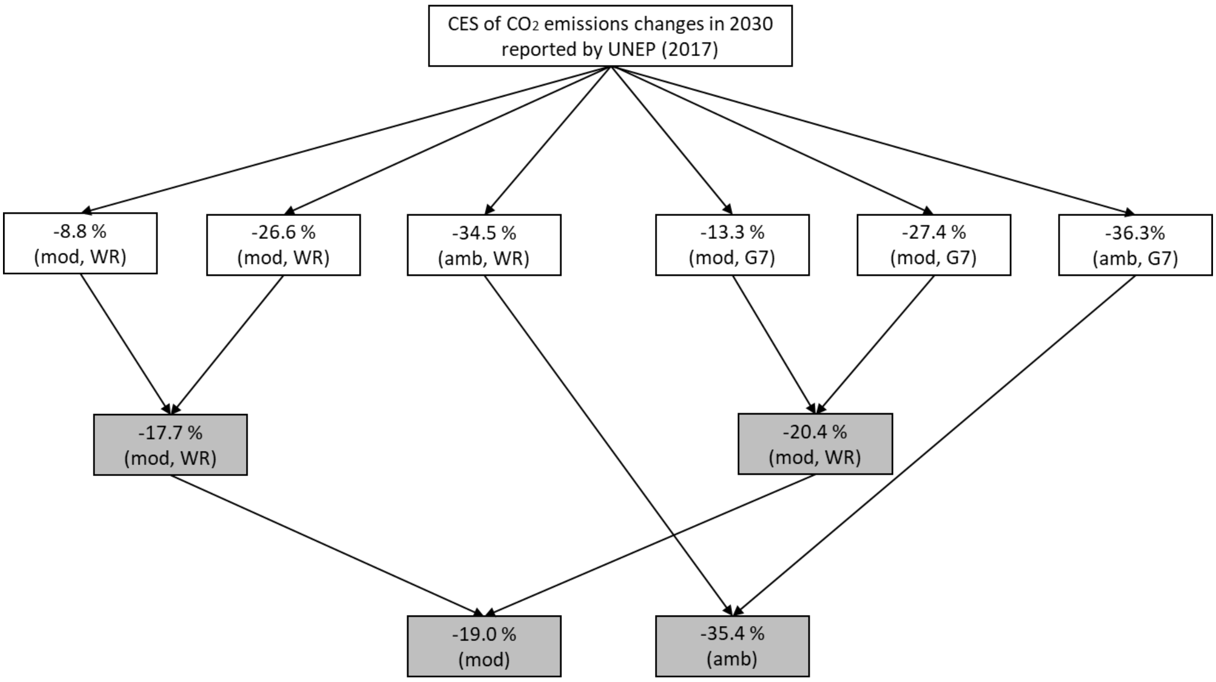

Figure 5.2. Example of data harmonization using the values reported by UNEP (UNEP, 2017). Numerical values represent changes in CO_2. Texts in parenthesis indicate scenario type and country/region. Abbreviations: mod = moderate scenarios; amb = ambitious scenarios; WR = world; G7 = Group of Seven (i.e. Canada, France, Germany, Italy, Japan, the United Kingdom and the United States). Solid blocks in grey indicate the calculated average of each scenario type.

Note that not all studies cover all years from 2020 to 2050 and not all studies cover the three types of impact (GDP, employment, and CO_2). File results_time_ser.xlsx in Supplementary Material presents the details of how many ambitious and moderate CES are available for each year and impact type.

To analyze the trajectory of macroeconomic, social, and environmental impacts, we plotted the changes in GDP, job creation, and CO_2 emissions from 2020 to 2050, as reported in the Results section. There, we also report the median, minimum and maximum values, and the interquartile range (IQR) as a measure of statistical dispersion.

We applied a traditional Pearson product-moment correlation coefficient (r) to analyze if the association between the changes in GDP, job creation, and CO_2 emissions is positive or negative. This method also allows us to identify the strength of a linear connection between the indicators (Rodgers & Nicewander, 1988). It is important to notice that a 'win-win' situation for some indicators involves different sign values of r. For instance, a correlation between GDP and employment can be interpreted as a 'win-win' if GDP and employment increased simultaneously, which is indicated by a positive Pearson correlation coefficient ($0 < r \leq 1$). In contrast, a 'win-win' in terms of macroeconomic and environmental impacts can be interpreted as an increase of GDP while CO_2 emissions are reduced, which would imply a negative Pearson correlation coefficient ($-1 \leq r < 0$).

Data sources and the Python code used for the meta-analysis are provided in Supplementary Material, in online version at: DOI: 10.5281/zenodo.3820181.

5.3. Results

We now assess the macroeconomic, social, and environmental impacts of a circularity transition reported by the selected literature, using as metrics changes in GDP, job creation, and CO_2 emissions. First, we present the trajectories of moderate and ambitious CESs from 2020 up to 2050. Second, we perform a statistical analysis of CESs in 2030. Finally, we perform a correlation analysis to determine if a circularity transition could contribute to a 'win-win-win' situation for macroeconomic, social, and environmental impacts in 2030.

5.3.1. Trajectory of changes in GDP, job creation, and CO_2 emissions for 2020-2050

Figure 5.3 presents the range of changes in GDP, job creation, and CO2 emissions calculated in the selected publications. The results are reported in relation to each study's business-as-usual (BAU) scenario (see equation [5.1]).

The trajectories of ambitious CESs for GDP (figure 5.3.a) are characterized by a wide range of values, varying from -0.1% (Cambridge Econometrics, European Commission, 2014) to 14.0% (Distelkamp et al., 2010). In general, the impacts of CESs on GDP are expected to be positive, as the median value rises from 0.2% in 2020 to 3.0% in 2050. In contrast, moderate CESs present a narrow range of impacts on GDP, ranging from 0.0% (Rademaekers et al., 2017) to 2.5% (Lee, 2018), and remaining almost constant through time (from a median of 0.0% in 2020 to 0.7% in 2050).

In a similar way, the effects of ambitious CESs on employment (figure 5.3.b) show an increase of job creation from a median of 0.9% in 2020 to 4.1% in 2050, while the impacts on employment in moderate scenarios are negligible, with a median of 0.0%. However, the trajectories from 2030 onwards only rely on 2 ambitious scenarios estimated by Meyer et al. (2015) and the Ellen MacArthur Foundation (EMF, 2015), and on moderate scenarios presented by Bosello et al. (2016) and the Ellen MacArthur Foundation (2015). Due to the limited number of CESs assessing employment after 2030, there is not enough data to perform a statistical analysis on that time period.

Regarding CO_2 emissions, CESs show a decrease in CO_2 emissions in both ambitious and moderate scenarios. The decrease of CO_2 emissions in ambitious scenarios ranges from -0.1% (Tuladhar et al., 2016) to -71.0% (EEA, 2014), with median values varying from -2.5% in 2020 to -55.3% in 2050. Likewise, CO_2 emissions in moderate scenarios fluctuate between 0.1% (Tuladhar et al., 2016) and -45.6% (UNEP, 2017), with a median value of -0.4% in 2020, and -37.4% in 2050.

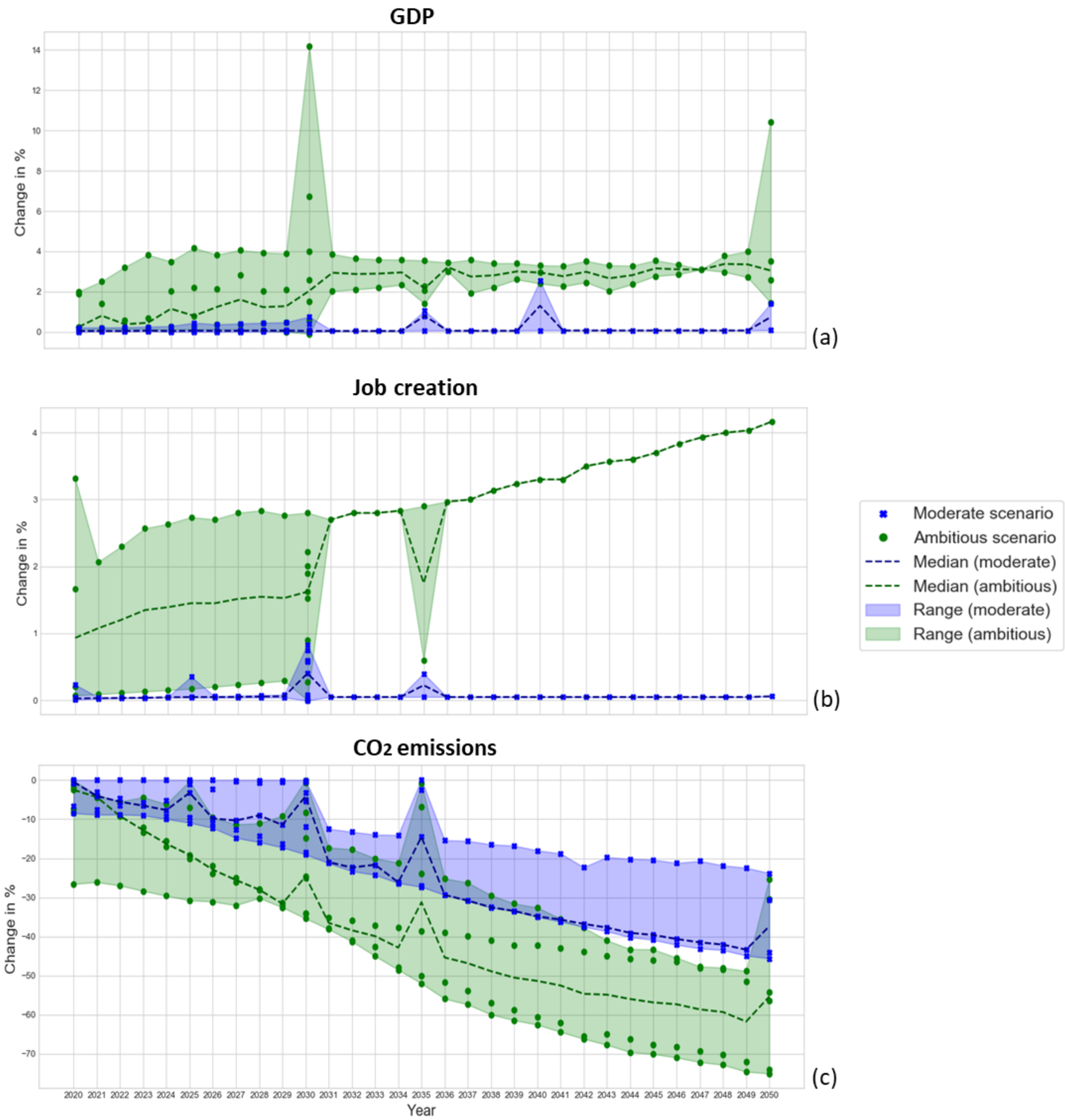

Figure 5.3. Range of changes in (a) GDP, (b) job creation, and (c) CO_2 emissions from 2020 to 2050 as estimated in the selected studies. Blue crosses indicate the values of moderate scenarios in each study. Green dots indicate the values of ambitious scenarios in each study. Blue and green dashed lines denote the median of moderate and ambitious scenarios in each year, respectively. Light blue and green areas denote the range between the maximum and minimum values for moderate and ambitious scenarios per year, respectively.

5.3.2. The macroeconomic, social, and environmental impacts of circularity up to 2030

We can use the trajectories presented above to assess the macroeconomic, social, and environmental implications of circularity in a specific period. Due to the fact that most of the scenarios were modelled in 2030 (with 9 of10 publications related to each indicator per scenario type), we perform a statistical analysis for the results in this year. Figure 4 presents a boxplot of CES impacts in 2030 summarizing the changes in GDP, job creation, and CO_2

emissions per scenarios type in the selected publications. The values of each CES are reported in relation to values of the respective BAU scenario in 2030.

The median ambitious CESs value for changes in GDP corresponds to 2.0% growth, with an interquartile range (IQR) between 0.4% and 4.6%. Most of the studies focused on impacts within the EU, with GDP scenarios varying from 0.0% to 0.6% at the country level (CE, 2018; Rademaekers et al., 2017), and from 2.8% to 6.7% at the regional level (Ellen MacArthur Foundation, 2015; B. Meyer et al., 2015). The other studies present the impacts on a global scale, with the most optimistic scenarios expecting a mean global GDP increase of 5.8% (B. Meyer et al., 2015; M. Meyer et al., 2018). An outlier value results from Distelkamp et al. (2010), as the authors reported a 14.0% increase of GDP in Germany due to resource efficiency interventions.

In moderate scenarios for GDP, no significant difference was found between CESs and BAU scenarios in 2030, with a median increase of 0.1% (IQR = [0.0 – 0.3] %). At the country level, Winning et al. (2017) assessed the macroeconomic impacts of moderate CESs in the iron and steel sectors of different nations, such as China (0.3%), Brazil (0.2%), Japan (0.1%), and the United States (0.0%). Furthermore, GDP change in moderate CESs for the EU region ranges from -0.0% to 0.4% (Cambridge Econometrics, European Commission, 2014; Rademaekers et al., 2017), and global GDP is estimated to increase by 0.02% (in Winning et al., 2017).

Regarding employment, the median value of increase in ambitious scenarios is 1.6% (IQR = [0.9 – 2.0] %). Employment in EU countries is expected to rise between 0.3% and 2.8% (CE, 2018; B. Meyer et al., 2015). Likewise, at the regional level, circularity interventions can contribute to an increase in employment by 0.0% to 2.8% (CE, 2018; Groothuis, 2016; Rademaekers et al., 2017). Nevertheless, the CESs explored by Wiebe et al. (2019) suggests that there could be a trade-off in job creation between regions. For instance, a CES resulting in 2.7% increase of jobs within the EU might lead to job creation in Asian economies ranging from -2.6% to 4.3%. Moreover, the overall effect of ambitious scenarios on job creation at the global scale is an increase of employment of 2.2% (Wiebe et al., 2019).

The impact of a moderate CESs on employment in 2030 is negligible, with a median of 0.1% (IQR = [0.0 – 0.4] %). The literature related to the impacts of moderate CESs on employment only reported on case studies in the EU. At the national level, moderate CESs could increase jobs by 0.0% to 0.7% (Distelkamp et al., 2010; Wijkman et al., 2015). In a similar way, the impacts of moderate CESs on job creation at the regional level vary between 0.0% and 0.8% (Beasley & Georgeson, 2014; Bosello et al., 2016; Cambridge Econometrics European Commission, 2014; Rademaekers et al., 2017).

Regarding CO_2 emissions, the median impact of ambitious CESs shows a reduction of -24.6% (IQR = - [34.0 – 8.2] %). A small number of studies reported on ambitious CESs in specific countries, with CO_2 emissions varying from -0.6% to -1.7% (Schandl et al., 2016; Tuladhar et al., 2016). In contrast, a larger number of studies modelled the CO_2 impacts of ambitious CESs on the regional scale, reporting reductions of -36.3% and -20.2% (Meyer et al., 2015; UNEP, 2017) for the EU and the Group of Seven (i.e. Canada, France, Germany, Italy, Japan, United Kingdom, and United States), respectively. The expected global impact of ambitious CESs on CO_2 emissions is to reduce emissions between -34.0% and -6.5% (Hatfield-Dodds et al., 2017; B. Meyer et al., 2015; Schandl et al., 2016).

The median value of the impact of moderate CESs on CO_2 emissions is -4.1% (IQR = - [10.2 – 0.3] %). At the country level, the impacts of moderate scenarios range between -5.4% and -0.3% (Wijkman et al., 2015; Xuan & Yue, 2017). Regional moderate CESs show that a -0.3% to -0.1% decrease of CO_2 emissions can be expected from circularity interventions in the EU (Beasley & Georgeson, 2014; Rademaekers et al., 2017). The expected impacts of moderate CESs on CO_2 emissions at the global level amount to a decrease of -14.0% (Hatfield-Dodds et al., 2017; M. Meyer et al., 2018; Winning et al., 2017).

It is important to notice that the results of CO_2 scenarios depend on the type of allocation used by the studies, and on whether the analysis is focused on production- or consumption-based CO_2 emissions. Most of the studies assessed production-based emissions, allocating the impacts to territorial emissions from economic activities. We found only one study related to carbon emissions from a consumption perspective. Schandl et al. (2016) presented their results as the direct and indirect CO_2 emissions (i.e. carbon footprint) in a country or region, and identified which carbon footprints were increased due to a circularity transition. For example, according to Schandl et al. (2016), the carbon footprints of Japan and the EU are expected to increase by 8.0% compared to the BAU scenarios resulting from the overall effect of circularity interventions up to 2030.

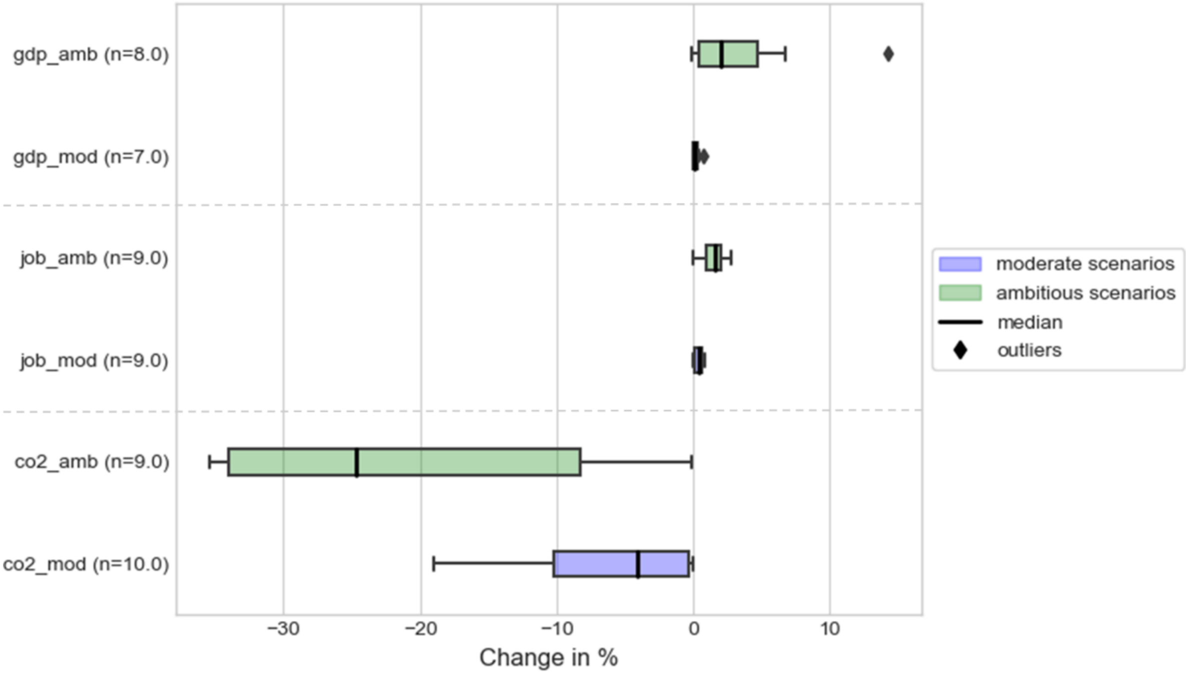

Figure 5.4. Boxplot of circular economy scenario impacts on GDP, job creation, and CO_2 emissions for 2030. gdp_amb and gdp_mod denote ambitious and moderate scenarios for GDP, respectively. job_amb and job_mod denote ambitious and moderate scenarios for job creation, respectively. co2_amb and co2_mod denote ambitious and moderate scenarios for CO_2 emissions, respectively. n indicates the number of studies in each category. Blue and green box indicate the range of moderate and ambitious scenarios, respectively. Diamond markers represent outliers, i.e. values which are away from 1.5 times the 1st or the 3rd quartile.

5.3.3. Does the circular economy lead to a 'win-win-win' situation?

Table 5.2 presents the correlation analysis of GDP increase, job creation, and CO_2 emissions in 2030. We use the Pearson correlation coefficient (r) as a measure of positive or negative relation between the indicators, and determine if a circularity transition could contribute to a 'win-win-win' situation in terms of macroeconomic, social and environmental impacts. Our findings show that there is a positive relation between GDP increase and job creation (r = 0.65), which means that if one CES leads to a higher GDP than another CES, then it is also expected to lead to more employment. CO_2 emissions are negatively related to GDP increase (r = -0.60) and job creation (r = -0.58), which means that if a CES leads to higher GDP or more jobs than another CES, it is expected to lead to less emissions. Thus, we observe that a circularity transition could lead to a 'win-win-win' situation for macroeconomic, social, and environmental impacts.

Table 5.2. Correlations between GDP, job creation, and CO_2 emissions in 2030

Correlated variables	**Pearson correlation coefficient (r)**	**Outcome**
GDP & Job	0.65	Win
GDP & CO_2	-0.60	Win
Job & CO_2	-0.58	Win

In order to better understand the relation between the indicators and whether a CES could drive a 'win-win-win' situation, we acknowledge that it is relevant to determine trade-offs across countries as well as to distinguish between specific circularity interventions. However, these aspects were not assessed due to the lack of information available in the CESs.

5.4. Discussion

Our meta-analysis showed that CESs are expected to increase GDP and employment while reducing CO_2 emissions. We focused on prospective studies that model exploratory scenarios. This means that CESs are not predictions, but rather a set of 'what-if' scenarios in which a circularity transition might change the impacts in comparison to a baseline scenario. Considering the exploratory nature of these studies, we now discuss the modelling features reported in the literature that yield the most favorable changes in GDP, job creation, and CO_2 emissions.

5.4.1. Key modelling features

A CES is developed by implementing multiple circularity interventions, whose general goal is to substitute primary materials with secondary materials and long-lasting products and which are modelled for specific features. For example, in the circular intervention of closing supply chains, the modelling feature can be changing the demand of resources for an economic activity, replacing the use of raw materials with the use of secondary materials. A detailed list of the modelling features used in each study is available in the worksheet selected_literature in file data_source.xlsx of the Supplementary Material. We now discuss the modelling features suggested by the literature that generate the larger changes in GDP, job creation, and CO_2 emissions. These key modelling features are resource taxes, technology change, and changes in consumption patterns.

Resource taxes (e.g. carbon tax, taxes on raw materials, such as metals and fossil fuels, and taxes on building materials) are used in the models to provide incentives for decreasing raw material extraction by increasing production costs and material/product prices. The revenues from the new taxes are usually allocated to material recovery activities (e.g. recycling activities) or reintroduced as R&D investment in material efficiency (Bosello et al., 2016; Cambridge Econometrics, European Commission, 2014; Hatfield-Dodds et al., 2017). As mentioned by McCarthy et al. (McCarthy et al., 2018), different studies apply resource taxes at multiple levels of the supply chain. Notice that there are no studies that apply resource taxes at the level of material extraction activities (e.g., extraction of coal in mining); instead, resource taxes are collected from the material outputs of such activities (e.g., the sale of coal).

Technological change, specifically improvements in resource use efficiency, are modelled through changes in unitary production costs. For instance, the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015) modelled the improvement of resource use in the building sector by considering the cost of industrial and modular construction to be 50% lower than the cost of traditional building processes. In a similar way, many studies applied exogenous changes in production costs to reflect technological improvements (see, for example, Cambridge Econometrics, European Commission, 2014; M. Meyer et al., 2018; Wijkman et al., 2015). An aspect that limits the modelling of technological change is that the level of resolution in macroeconomic and structural models does not allow to model specific secondary and waste treatment activities. In other words, the high level of aggregation restricts the options of technological innovation (de Koning, 2018; McCarthy et al., 2018).

Another key modelling feature found in several studies is changing consumption patterns (or behavioral change). For example, consumers will require smaller numbers of certain goods resulting from product lifetime extension and more sharing, which means that less materials are required to satisfy specific societal needs. In many cases, behavioral changes develop from the intrinsic motivation of individuals, with bottom-up actions leading to societal transformation. For example, Hu et al. (2015) found that scenarios with active citizen participation would drive the largest reduction of CO_2 emissions, although they showed a trade-off between environmental and socioeconomic impacts, as the reduction of CO_2 emissions was associated with decreases in GDP and employment. On the other hand, governments can also contribute to changes in consumption patterns using a top-down approach. This is the case if governments encourage citizens to develop circular economy activities, for example, by promoting consumer information campaigns focusing on waste reduction and repairing activities (Vita et al., 2019; Woltjer, 2018). With proper policy schemes, these activities can create new job opportunities while reducing environmental impacts.

Regardless of which modelling feature is implemented in a particular CES, our statistical analysis shows that the circularity transition is likely to generate only marginal or incremental socioeconomic changes. For instance, our median results show that in ambitious CESs, we can expect increases of 2.0% of GDP and 1.6% of job creation relative to a BAU in the year 2030. In contrast, CO_2 emission reduction seems to be highly optimistic with a median of -24.6% for ambitious scenarios. Nevertheless, the ambitious scenarios for CO_2 emissions showed the largest spread of CES values (with interquartile ranges ranging from -34.0% to -8.2%), which means that results can vary significantly between studies.

We believe that a circularity transition will not yield a radical transformation of resource use and its impacts in the upcoming decade (as was also suggested by Tukker and Ekins, 2019). Thus, the implementation of circularity interventions could generate a 'win-win-win' situation with respect to GDP, job creation and CO_2 emissions, but these gains will be incremental.

5.4.2. Limitations and further research

Each approach to modeling the impacts of circularity interventions has specific strengths and weaknesses. However, we notice various modelling limitations that are recurrent across the literature: public investments, rebound effects, and policy interventions.

There is limited information about how much public investment is required to implement specific circularity interventions. Only a few studies modelled public investment to some degree, by using exogenous parameters related to capital stock, investments on R&D and consulting services (Best et al., 2018; McCarthy et al., 2018). Although there is no consensus about how much policy effort is required, we find that most studies acknowledge in a qualitative way that some degree of public investment is required. For example, Wijkman and Skånberg (2015) suggest that a circularity transition would require public investment on infrastructure involving a transitory increase of employment, material use and CO_2 emissions. We consider that further assessment of the impacts of circular economy policies can be improved by the explicit inclusion of a transition phase.

Secondly, current modelling of CESs is limited in terms of understanding rebound effects. The savings from a more resource-efficient and circular economy could result in more consumption, depending on how such savings are re-expended by consumers (Best et al., 2018; Zink & Geyer, 2017). According to some CESs, jobs and CO_2 emissions could shift between countries, affecting other regions and creating negative effects on society and the environment overall (Bosello et al., 2016; Wiebe et al., 2019). The rebound effect of CESs is discussed in some studies (European Commission, 2014; M. Meyer et al., 2018; UNEP, 2017). Nevertheless, there is still little quantitative analysis of the potential magnitude of rebound effects, and how to prevent their potential negative environmental impacts.

Thirdly, the modelling of circular economy policies has been focused on what-if future exploratory scenarios. However, it is still not clear which measures should be implemented at the present time to achieve the potential benefits of circular economy policies. Assessing circularity from the normative perspective could generate insights into which economic sectors are more relevant for implementing circularity interventions, thus supporting the decision-making process. Future studies might also use a backcasting approach, which makes it possible to assess current opportunities in order to achieve circularity targets in the middle and long term.

Finally, it is important to notice that the correlation analysis in this study does not differentiate between the studies' geographical scopes. We did not distinguish between specific countries or regions because there were not enough values per country or region to perform a proper correlation analysis.

As the majority of studies included in the present meta-analysis focused on one economy without considering the impacts on other countries or regions, the correlation analysis does not consider trade-offs between economies. For instance, an increase of jobs linked to repair activities in the EU would negatively impact primary production in other countries, which would imply a reduction of employment elsewhere. In this case, repair may increase the number of jobs in the country where products are repaired, but may lead to a greater reduction in jobs in countries where the primary production takes place. This type of trade-off between countries cannot be captured by the outcomes shown in table 2, which is a limitation of the present correlation analysis.

Moreover, we recognize that specific circularity interventions could lead to different results for the Pearson correlation coefficient (r). For example, the implementation of product lifetime extension might generate job losses (if more durable goods lead to a reduction in the demand for primary production) as well as reduce CO_2 emissions (if there are no high use-phase emissions), which would imply a 'lose-win' situation in terms of social and environmental impacts. However, we could not differentiate between circularity interventions in the correlation analysis because the results presented by the literature were highly aggregated in terms of circularity interventions. That is, sometimes a single CES outcome was reported that in fact resulted from multiple circularity interventions, whose individual impacts could not be isolated.

5.5. Conclusion

The purpose of this chapter was to perform a meta-analysis of CESs to establish a consensus regarding the potential macroeconomic, social, and environmental impacts of a circularity transition. Previous articles at macro level (i.e. on national and multinational scales) have shown the impacts of circularity interventions on GDP, job creation and CO_2 emissions, but these studies did not correlate the macroeconomic, social and environmental indicators to determine whether circularity interventions could generate a 'win-win-win' situation. We filled this research gap by performing a statistical analysis of 300 CESs.

Our study analyzed the changes in GDP, job creation and CO_2 emissions estimated by means of models that implement CESs for the period up to 2050. We identified the trajectories of more than 300 CESs compared to the business-as-usual scenarios from 2020 to 2050, and assessed the range of changes in GDP, job creation and CO_2 emissions up to 2030. Furthermore, we performed a correlation analysis between the indicators of changes that can be achieved by 2030 to evaluate if a circularity transition would provide a 'win-win-win' situation regarding macroeconomic, social, and environmental impacts.

We also discussed the three modelling features identified across the studies that yield the most favorable changes in the macro-economic indicators: resource taxes, technology changes, and adapting consumption patterns. A common view proposed in the selected literature is that a circularity transition requires some degree of policy intervention and that it will generate incremental macroeconomic and social benefits, as well as more considerable environmental benefits.

We consider that follow-up research should focus on the enhancement of modelling CESs. This modelling can be improved by incorporating public investments and rebound effects in the analysis. Moreover, in order to support decision making, we find it relevant to consider a normative approach on circularity assessments, i.e., to identify key measures in the present that contribute to a more cost-effective circularity transition.

As different circularity interventions are likely to have different trade-offs, we recommend that studies should differentiate between different types of circularity intervention when analyzing environmental and economic trade-offs. Furthermore, we suggest that studies focusing on a single country or region may miss trade-offs on the global scale and may hence suggest win-win effects that may exist on the national or regional scale, but are absent on the global scale. Thus, we suggest that future studies should include such trade-offs between regions and countries, which implies that they must consider the global scale and present region- or country-specific advantages and disadvantages of the implementation of circularity interventions.

This chapter contributes to understanding the macro-level implications of circular economy policies, which can support decision makers and practitioners in recognizing the macroeconomic, social, and environmental implications of a circularity transition. Moreover, our outcomes can help researchers that model the circularity interventions by identifying the main modelling features and indicating ways to enhance the analysis of circularity interventions.

5.6. References

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions : a review of EEIOA-based studies. *Journal of Economic Structures, 7*(14), 1–24. https://doi.org/10.1186/s40008-018-0113-3

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2010). Material efficiency: A white paper. *"Resources, Conservation & Recycling," 55,* 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Beasley, J., & Georgeson, R. (2014). *Advancing resource efficiency in Europe. Indicators and waste policy scenarios to deliver a resource efficient and sustainable Europe.*

Beccarello, M., & Di Foggia, G. (2018). Moving towards a circular economy : economic impacts of higher material recycling targets. *Materials Today: Proceedings, 5*(1), 531–543. https://doi.org/10.1016/j.matpr.2017.11.115

Best, A., Duin, L., & Chelminske, M. (2018). *Macroeconomic and Societal Impacts of Mainstreaming the Circular Economy. Deliverable D5.3 Circular Impacts*.

Blanco, C. F., Cucurachi, S., Peijnenburg, W. J. G. M., Beames, A., & Vijver, M. G. (2020). Are Technological Developments Improving the Environmental Sustainability of Photovoltaic Electricity? *Energy Technology*, 1901064. https://doi.org/10.1002/ente.201901064

Böhringer, C., & Rutherford, T. F. (2015). *The Circular Economy – An Economic Impact Assessment Report to SUN-IZA. June,* 1–33. https://sunstiftungsfonds.files.wordpress.com/2015/06/report-circular-economy.pdf

Bonan, G. B., & Doney, S. C. (2018). Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. *Science, 359*(6375). https://doi.org/10.1126/science.aam8328

Bosello, F., Antosiewicz, M., Bukowski, M., Eboli, F., Gaske, J., Sniegocki, A., Witajewski-Baltvilks, J., & Zotti, J. (2016). *Report on Economic Quantitative Ex- Ante Assessment of DYNAMIX Policy Mixes. DYNAMIX Deliverable D6.2*.

CE. (2018). *Impacts of circular economy policies on the labour market. Final report*. https://doi.org/10.2779/574719

CI. (2018). *Library. Circular Impacts Project*.

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J.-C., Ley, D., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., & Sugiyama, T. (2018). *Strengthening and Implementing the Global Response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthen*.

de Koning, A. (2018). *Creating Global Scenarios of Environmental Impacts with Structural Economic Models* [Leiden University]. https://doi.org/ISBN: 978-94-90858-55-1

Distelkamp, M., Meyer, B., & Meyer, M. (2010). *Quantitative and qualitative Effects of a forced Resource Efficiency Strategy*.

Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*, 104508. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104508

EEA. (2014). *Resource-efficient green economy and EU policies.* https://doi.org/10.2800/18514

Ellen MacArthur Foundation. (2015). Growth within: a circular economy vision for a competitive Europe. In *Ellen MacArthur Foundation*. https://doi.org/Article

EMF. (2013). *Toward the circular economy. Technical Report*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

EMF. (2015). *Delivering the Circular Economy. A toolkit for policymakers*.

European Commission. (2014). Study on Modelling of the Economic and Environmental Impacts of Raw Material Consumption. In *Technical report 2014-2478* (Issue March). https://doi.org/10.2779/77904

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy - A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of Cleaner Production*, *23*, 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Groothuis, F. (2016). *New Era. New Plan. Europe. A fiscal strategy for an inclusive, circular economy*.

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., West, J., & Havlik, P. (2017). Assessing global resource use and greenhouse emissions to 2050 , with ambitious resource efficiency and climate mitigation policies. *Journal of Cleaner Production*, *144*, 403–414. https://doi.org/10.1016/j.jclepro.2016.12.170

Horváthová, E. (2010). Does environmental performance affect financial performance? A meta-analysis. *Ecological Economics*, *70*(1), 52–59. https://doi.org/10.1016/j.ecolecon.2010.04.004

Horváthová, E. (2012). The impact of environmental performance on firm performance: Short-term costs and long-term benefits? *Ecological Economics*, *84*, 91–97. https://doi.org/10.1016/j.ecolecon.2012.10.001

Hu, J., Moghayer, S., & Reynes, F. (2015). *Policy Options for a Resource-Efficient Economy. Report about integrated scenario interpretation EXIOMOD / LPJmL results. Deliverable D3.7b*.

IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel*.

Jin, Y., Behrens, P., Tukker, A., & Scherer, L. (2019). Water use of electricity technologies: A global meta-analysis. *Renewable and Sustainable Energy Reviews*, *115*, 109391. https://doi.org/10.1016/j.rser.2019.109391

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources , Conservation & Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Lee, D. (2018). Building evaluation model of biohydrogen industry with circular economy in Asian countries. *International Journal of Hydrogen Energy*, 1–12. https://doi.org/10.1016/j.ijhydene.2018.09.069

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Ioannidis, J. P. a, Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). Annals of Internal Medicine Academia and Clinic The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions : *Annals of Internal Medicine*, *151*(4), W65–W94. https://doi.org/10.1371/journal.pmed.1000100

Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology*, *21*(3), 545–558. https://doi.org/10.1111/jiec.12552

Luederitz, C., Meyer, M., Abson, D. J., Gralla, F., Lang, D. J., Rau, A. L., & Von Wehrden, H. (2016). Systematic student-driven literature reviews in sustainability science - An effective way to merge research and teaching. *Journal of Cleaner Production*, *119*, 229–235. https://doi.org/10.1016/j.jclepro.2016.02.005

Mayer, A., Haas, W., Wiedenhofer, D., Nuss, P., & Blengini, G. A. (2018). Measuring Progress towards a Circular Economy A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, *00*(0), 1–15. https://doi.org/10.1111/jiec.12809

McCarthy, A., Dellink, R., & Bibas, R. (2018). *The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches*.

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., & Doménech, T. (2017). Circular Economy Policies in China and Europe. *Journal of Industrial Ecology*, *21*(3), 651–661. https://doi.org/10.1111/jiec.12597

Meyer, B., Distelkamp, M., & Beringer, T. (2015). *Policy Options for a Resource-Efficient Economy. Report about integrated scenario interpretation GINFORS / LPJmL results. Deliverable D3.7a*.

Meyer, M., Hirschnitz-Garbers, M., & Distelkamp, M. (2018). Contemporary Resource Policy and Decoupling Trends — Lessons Learnt from Integrated Model-Based Assessments. *Sustainability*, *10*(1858), 1–28. https://doi.org/10.3390/su10061858

Mitchell, P., & Doherty, M. (2015). *Job Creation in the Circular Economy - Increasing Resource Efficiency in Northern Ireland*. https://doi.org/10.13140/RG.2.1.4647.3689

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., & Group, P. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, *4*(1), 1–9. https://doi.org/10.1186/2046-4053-4-1

Morgan, J., & Mitchell, P. (2015). *Opportunities to tackle Britain's labour market challenges through growth in the circular economy*.

Pan, S.-Y., Du, M. A., Huang, I.-T., Liu, I.-H., Chang, E.-E., & Chiang, P.-C. (2015). Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. *JOURNAL OF CLEANER PRODUCTION*, *108*, 409–421. https://doi.org/10.1016/j.jclepro.2015.06.124

Rademaekers, K., Svatikova, K., Vermeulen, J., Smit, T., & Baroni, L. (2017). *Environmental potential of the collaborative economy. Final Report and Annexes*. https://doi.org/10.2779/518554

Rodgers, J. L., & Nicewander, W. A. (1988). Thirteen Ways to Look at the Correlation Coefficient. *The American Statistician*, *42*(1), 59–66. https://doi.org/10.2307/2685263

Rohatgi, A. (2019). *WebPlotDigitizer (Version 4.2)*.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). *Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions*. https://doi.org/10.1016/j.jclepro.2015.06.100

Söderman, M. L., Eriksson, O., Björklund, A., Östblom, G., Ekvall, T., Finnveden, G., Arushanyan, Y., & Sundqvist, J. (2016). Integrated Economic and Environmental Assessment of Waste Policy Instruments. *Sustainability*, *8*(411), 1–21. https://doi.org/10.3390/su8050411

Tukker, A. (2015). Product services for a resource-efficient and circular economy - A review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

Tukker, A., & Ekins, P. (2019). Concepts Fostering Resource Efficiency : A Trade-off Between Ambitions and Viability. *Ecological Economics*, *155*, 36–45. https://doi.org/10.1016/j.ecolecon.2017.08.020

Tuladhar, S. D., Yuan, M., & Montgomery, W. D. (2016). An Economic Analysis of The Circular Economy. *The 19th Annual Conference on Global Economic Analysis "Analytical Foundations for Cooperation in a Multipolar World"*.

UNEP. (2017). *Resource Efficiency: Potential and Economic Implications. A report of the International Resource Panel. Technical Report.*

Valdivia, S., Ugaya, C. M. L., Hildenbrand, J., Traverso, M., Mazijn, B., & Sonnemann, G. (2013). A UNEP/SETAC approach towards a life cycle sustainability assessment - Our contribution to Rio+20. *International Journal of Life Cycle Assessment*, *18*(9), 1673–1685. https://doi.org/10.1007/s11367-012-0529-1

van Notten, P. (2006). Scenario Development: A Typology of Approaches. In *Think Scenarios, Rethink Education* (pp. 69–87). OECD Publishing. https://doi.org/10.1787/9789264023642-6-en

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

Vita, G., Hertwich, E. G., Stadler, K., & Wood, R. (2019). Connecting global emissions to fundamental human needs and their satisfaction Connecting global emissions to fundamental human needs and their satisfaction. *Environmental Research Letters*, *14*, 1–16. https://doi.org/10.1088/1748-9326/aae6e0

Wang, J., Rodrigues, J. F. D., Hu, M., Behrens, P., & Tukker, A. (2019). The evolution of Chinese industrial CO2 emissions 2000–2050: A review and meta-analysis of historical drivers, projections and policy goals. *Renewable and Sustainable Energy Reviews*, *116*. https://doi.org/10.1016/j.rser.2019.109433

WEF. (2014). Towards the Circular Economy : Accelerating the scale-up across global supply chains. In *World Economic Forum*. https://doi.org/10.1162/108819806775545321

Wiebe, K. S., Harsdorff, M., Montt, G., Simas, M. S., & Wood, R. (2019). Global Circular Economy Scenario in a Multiregional Input-Output Framework. *Environmetal Science & Technology*, *56*(11), 6362–6373. https://doi.org/10.1021/acs.est.9b01208

Wijkman, A., Skånberg, K., & Berglund, M. (2015). *The Circular Economy and Benefits for Society Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency*. https://www.clubofrome.org/wp-content/uploads/2016/03/The-Circular-Economy-and-Benefits-for-Society.pdf

Winning, M., Calzadilla, A., Bleischwitz, R., & Nechifor, V. (2017). Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. *International Economics and Economic Policy*. https://doi.org/10.1007/s10368-017-0385-3

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14*, 1–10. https://doi.org/10.1145/2601248.2601268

Woltjer, G. (2018). *Scenario Analysis for a Circular Economy. Deliverable D5.1 Circular Impacts*.

Xuan, Y., & Yue, Q. (2017). Scenario analysis on resource and environmental benefits of imported steel scrap for China's steel industry. *Resources, Conservation & Recycling*, *120*, 186–198. https://doi.org/10.1016/j.resconrec.2016.12.011

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *In Press*(0), 1–10. https://doi.org/10.1111/jiec.12545

Zumsteg, J. M., Cooper, J. S., & Noon, M. S. (2012). Systematic Review Checklist: A

Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data. *Journal of Industrial Ecology*, *16*(SUPPL.1). https://doi.org/10.1111/j.1530-9290.2012.00476.x

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.

6.5. References

Casella, B., Bolwijn, R., Moran, D., & Kanemoto, K. (2019). UNCTAD insights: Improving the analysis of global value chains: the UNCTAD-Eora Database. *Transnational Corporations*, *26*(3), 115–142. https://doi.org/10.18356/3aad0f6a-en

Cullen, J. M. (2017). Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *Journal of Industrial Ecology*, *00*(0), 1–4. https://doi.org/10.1111/jiec.12599

de Koning, A. (2018). *Creating Global Scenarios of Environmental Impacts with Structural Economic Models* [Leiden University]. https://doi.org/ISBN: 978-94-90858-55-1

de Wit, M., Hoogzaad, J., Ramkumar, S., & Friedl, H. (2018). *The Circularity Gap report*.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Duchin, F., Levine, S. H., & Strømman, A. H. (2016). Combining Multiregional Input-Output Analysis with a World Trade Model for Evaluating Scenarios for Sustainable Use of Global Resources, Part I: Conceptual Framework. *Journal of Industrial Ecology*, *20*(4), 775–782. https://doi.org/10.1111/jiec.12303

EC. (2020). *Circular Economy Action Plan: For a cleaner and more competitive Europe*. https://ec.europa.eu/environment/circular-economy/

EMF. (2013). *Toward the circular economy. Technical Report*. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Fellner, J., Lederer, J., Scharff, C., & Laner, D. (2017). Present Potentials and Limitations of a Circular Economy with Respect to Primary Raw Material Demand. *Journal of Industrial Ecology*, *21*(3), 494–496. https://doi.org/10.1111/jiec.12582

Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., & Owen, A. (2019). The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO. *Journal of Industrial Ecology*, *23*(4). https://doi.org/10.1111/jiec.12833

Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020). Spaceship earth's odyssey to a circular economy - a century long perspective. *Resources, Conservation and Recycling*, *163*(August), 105076. https://doi.org/10.1016/j.resconrec.2020.105076

IRP. (2019). *Global Resource Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel*. https://www.resourcepanel.org/reports/global-resources-outlook

Krausmann, F., Wiedenhofer, D., & Haberl, H. (2020). Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. *Global Environmental Change*, *61*(May 2019), 102034. https://doi.org/10.1016/j.gloenvcha.2020.102034

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., & Fishman, T. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS*, *114*(8), 21–26. https://doi.org/10.1073/pnas.1613773114

Lenzen, M., & Reynolds, C. J. (2014). A Supply-Use Approach to Waste Input-Output Analysis. *Journal of Industrial Ecology*, *18*(2), 212–226. https://doi.org/10.1111/jiec.12105

Lenzen, M., Wood, R., & Wiedmann, T. (2010). Uncertainty analysis for multi-region input - output models - a case study of the UK'S carbon footprint. *Economic Systems Research*, *22*(1), 43–63. https://doi.org/10.1080/09535311003661226

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2020). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825

Merciai, S., & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *00*(0), 1–16. https://doi.org/10.1111/jiec.12713

Nakamura, Nakajima, K., Kondo, Y., & Nagasaka, T. (2007). The waste input-output approach to materials flow analysis - Concepts and application to base metals. *Journal of Industrial Ecology*, *11*(4), 50–63. https://doi.org/10.1162/jiec.2007.1290

OECD. (2017). *The macroeconomics of the circular economy transition* (Vol. 33). https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPRPW/WPIEEP(2017)1/FINAL&docLanguage=En

Owen, A., Steen-Olsen, K., Barrett, J., Wiedmann, T., & Lenzen, M. (2014). A Structural Decomposition Approach To Comparing MRIO Databases. *Economic Systems Research*, *26*(3), 262–283. https://doi.org/10.1080/09535314.2014.935299

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *NATURE CLIMATE CHANGE*, *7*(1), 13–20. https://doi.org/10.1038/NCLIMATE3148

Pauliuk, S., Fishman, T., Heeren, N., Berrill, P., Tu, Q., Wolfram, P., & Hertwich, E. G. (2020). Linking service provision to material cycles: A new framework for studying the resource efficiency–climate change (RECC) nexus. *Journal of Industrial Ecology*, 1–14. https://doi.org/10.1111/jiec.13023

Reynolds, C. J., Piantadosi, J., & Boland, J. (2014). A Waste Supply-Use Analysis of Australian Waste Flows. *Journal of Economic Structures*, *3*(1), 5. https://doi.org/10.1186/s40008-014-0005-0

Salemdeeb, R., Al-tabbaa, A., & Reynolds, C. (2016). The UK waste input – output table: Linking waste generation to the UK economy. *Waste Management & Research*, *34*(10), 1089–1094. https://doi.org/10.1177/0734242X16658545

Schmidt, J., & Merciai, S. (2017). *Physical/hybrid supply and use tables – methodological report. DESIRE deliverable*. http://fp7desire.eu/documents/category/3-public-deliverables

Sigüenza, C. P., Steubing, B., Tukker, A., & Aguilar-Hernández, G. A. (2020). The environmental and material implications of circular transitions: A diffusion and product-life-cycle-based modeling framework. *Journal of Industrial Ecology*, 1–17. https://doi.org/10.1111/jiec.13072

Södersten, C. J., Wood, R., & Hertwich, E. G. (2018a). Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting. *Environmental Science and Technology*, *52*(22), 13250–13259. https://doi.org/10.1021/acs.est.8b02791

Södersten, C. J., Wood, R., & Hertwich, E. G. (2018b). Environmental Impacts of Capital Formation. *Journal of Industrial Ecology*, *22*(1), 55–67. https://doi.org/10.1111/jiec.12532

Södersten, C. J., Wood, R., & Wiedmann, T. (2020). The capital load of global material footprints. *Resources, Conservation and Recycling*, *158*, 104811. https://doi.org/10.1016/j.resconrec.2020.104811

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and Waste Footprints. *Journal of Industrial Ecology*, *00*(0), 1–13. https://doi.org/10.1111/jiec.12562

Tukker, A., de Koning, A., Owen, A., Lutter, S., Bruckner, M., Giljum, S., Stadler, K., Wood, R., & Hoekstra, R. (2018). Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. *Journal of Industrial Ecology*, *22*(3), 585–598. https://doi.org/10.1111/jiec.12716

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting : Concepts , Modelling , and Global Application for 1900 – 2050. *Ecological Economics*, *156*, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010

Winning, M., Calzadilla, A., Bleischwitz, R., & Nechifor, V. (2017). Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. *International Economics and Economic Policy*. https://doi.org/10.1007/s10368-017-0385-3

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *In Press*(0), 1–10. https://doi.org/10.1111/jiec.12545

Summary

A sustainable resource management is an essential aspect to satisfy the current human needs without compromising the needs of future generations. However, there are several challenges for achieving resource use in sustainable way. For example, the increase of resource extraction as well as disruptive events (e.g. natural disasters, or financial crisis) are two of the aspects that affect resource availability and accessibility. Thus, there is a need to provide resource-efficient strategies that enables to decrease the risk of disruptive supply chains while maintaining natural resources for the current and future generations. Within this context, circular economy has been proposed as a paradigm that aims to reduce resource extraction and waste flows by retaining materials into the economy. Furthermore, there are multiple actions or processes that lead material circularity and a sustainable - here called circularity interventions – in which researchers and practitioners have proposed effective strategies to achieve a sustainable resource management.

From global perspective, it becomes crucial to understand whether circularity interventions could lead to macroeconomic, social, and environmental benefits. This has led to a growing body of literature that assess the global material inflows and outflows, providing a global picture of resource use and its economic and environmental implications. However, there is still a lack of understanding on how a global circularity transition might look like, and what would be the magnitude of the potential economic, social, and environmental implications of material circularity on macro scale. These aspects raise the questions: is circular economy a sustainable solution to achieve a global economic and environmental sustainability? And what are the macroeconomic, social, and environmental implications of a transition to a circular economy?

A macro level assessment of material circularity aims to assess whether circularity interventions could contribute to a sustainable resource management, and explore which circularity interventions could contribute to a cost-effective circularity transition on a macro scale. In this matter, environmentally extended input-output analysis (EEIOA) has been used as consistent framework to assess potential macroeconomic and environmental impacts. In contrast with other methods (e.g. life cycle assessment (LCA) and material flow analysis (MFA)), EEIOA method brings the advantage of incorporating the size and structure of an economy, in which circularity interventions can be evaluated in a comprehensive way.

To address the main aim, there are three aspects that require to addressed. First, although EEIOA brings a suitable framework to assess material circularity, it is important to understand how to apply EEIOA in the assessment of circularity interventions. Second, there is a lack of information about the potential materials that can be used for a global material circularity. Third, there is a need to determine what could be the potential macroeconomic, social, and environmental impacts of material circularity. To fulfil the mentioned aspects, Chapter 1 to 5 offered answers to each research question mentioned below, as follows:

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

To answer RQ1 question, Chapter 2 brought a systematic literature review of EEIOA-based studies on the assessment of material circularity. This Chapter presented over 90 publications

that assess circularity interventions, which were analyzed in terms of the opportunities and limitations of applying EEIOA method. Based on the reviewed literature, a consensus on how to model circularity interventions using EEIOA was established. Likewise, Chapter 2 showed how each circularity intervention requires different ways to adjust intermediate and final demand coefficients, and the integration of multiple data in input-output tables. Overall, general, an effective assessment of 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.

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

To address RQ2 question, Chapter 3 presented an estimation of the circularity gap of 43 countries and 5 rest of the world regions in 2011, using the global, multiregional, hybrid-units input-output tables (MR-HIOT) EXIOBASE. This Chapter also redefined the circularity gap as waste generation plus waste generated from previous in-use stocks (i.e. stock depletion) minus waste recovery, which represents the amount of unrecovered waste available for recovery or recycling in a specific period. The global material inflows amounted to 77 Gt in 2011, which was constituted of 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 was 9 Gt in this period, and 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. Furthermore, the circularity gap varied with respect to the level of economic development, where high income regions presented larger circularity gap per capita compared with middle and lower middle income countries. Finally, Chapter 3 discussed how to implement the circularity interventions described in Chapter 2 to minimize the circularity gap of each country and region.

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

Chapter 4 brought an answer to RQ3 by estimating the global distribution of material added to in-use stocks. This Chapter showed a high geographical, material type, and sectoral distribution of material inflows to in-use stocks across 43 countries and 5 rest of world using the MR-HIOT EXIOBASE. As mentioned in Chapter 3, global material added to in-use stocks amounted to 30 Gt in 2011. Based on the geographical distribution, high income countries and some emerging economies (e.g. China) amounted for almost 70% of material inflows to in-use stocks in 2011, also having the highest stock additions per capita worldwide. For material types, stock additions 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%). For sectoral distribution, construction sector comprised around 90% of non-metallic minerals, which highlights the relevance of implementing circularity interventions for the construction sector. Chapter 4 also discussed the application of circularity interventions from Chapter 2 to identify which circularity interventions can be used for a sustainable management of material inflows to in-use stocks in the shortest- and long-term.

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

To answer RQ4, Chapter 5 presented a systematic literature review and meta-analysis of publications that analyze the potential changes in GDP, employment, and carbon emissions generated by the adoption of circularity interventions (i.e. circularity transition). Chapter 5 covered over 300 circular economy scenarios (CESs) from 2020 up to 2050, which were reviewed and harmonized to perform a statistical analysis to determine whether circularity interventions could lead to a 'win-win-win' situation in terms of macroeconomic, social, and environmental impacts. Based on the reviewed CESs for 2030, circularity interventions could lead to incremental changes in GDP (median (mdn) = 2.0%; interquartile range (IQR) = [0.4–4.6]%), and job creation (mdn = 1.6%; IQR = [0.9–2.0]%), while changes in CO_2 emissions could be more substantial (mdn = -24.6%), but values are largely spread (IQR = -[34.0–8.2]%).Moreover, Chapter 5 discussed the 3 main modelling features applied in CESs (i.e. resource taxes, technological and consumption pattern changes), as well as which additional modelling features are required to enhance the assessment of material circularity at macro scale.

Overall, Chapter 2 to 5 showed that material circularity play an important role for a sustainable resource management. Nevertheless, material circularity by itself will not be enough to address global sustainability issues. For instance, the current amount of waste available for circularity is not enough to satisfy the demand of new goods and services. This is because global material inflows to in-use stocks are higher than the materials removed from in-use stocks. Furthermore, material circularity has a limited contribution to decrease material extraction for food and energy purposes, because food and energy flows cannot be reintroduced into the economy as other durable goods. To address sustainable resource management, it would be required the integration of other existing strategies from other systems (e.g. food and renewable energy) together with circularity interventions.

A macro level assessment of material circularity contributes to bring a better understanding of the opportunities and limitations of applying EEIOA on the assessment of material circularity; how circularity interventions can be used by multiple countries or regions; and a consensus of the macroeconomic, social, and environmental impacts of a circularity transition.

Furthermore, the use of MR-HIOT EXIOBASE provided an important advance on the assessment of material circularity because it avoids the disconnection between monetary and physical values of waste flows and other material flows with the highest level of resolution up to date. Further research on material circularity should focus on improving the MR-HIOT EXIOBASE in terms of data resolution, waste accounts, time series, stock accounts and stock-flow modelling, dynamic modelling, and data uncertainty. These aspects will lead to a more comprehensive information that can be used to support decision makers on implementing circularity interventions in more cost-effective way.

Samenvatting

Een duurzaam beheer van natuurlijke hulpbronnen is essentieel om aan de huidige menselijke behoeften te voldoen zonder de behoeften van toekomstige generaties in gevaar te brengen. Er zijn echter verschillende uitdagingen om op een duurzame manier gebruik te maken van zulke hulpbronnen. De groei van het gebruik van grondstoffen en ontwrichtende gebeurtenissen (bv. natuurrampen of financiële crises) zijn twee aspecten die het evenwicht tussen vraag en aanbod van hulpbronnen beïnvloeden. Er is dus behoefte aan strategieën die het mogelijk maken om het risico van leveringszekerheid van grondstoffen te verkleinen en tegelijkertijd de beschikbaarheid van zulke hulpbronnen voor de huidige en toekomstige generaties te verzekeren. Tegen deze achtergrond is het concept van de Circulaire economie ontwikkeld. Circulaire economie is er op gericht om de noodzaak van gebruik van primaire grondstoffen te verminderen, en het ontstaan van afval te voorkomen, door materialen zo lang mogelijk in de economie in gebruik te houden. We noemen ingrepen om tot een circulaire economie in dit proefschrift circulariteitsinterventies.

Het is daarbij cruciaal om te begrijpen of en zo ja welke circulariteitsinterventies kunnen leiden tot macro-economische, sociale en ecologische voordelen. Dit heeft geleid tot een groeiende hoeveelheid literatuur die de wereldwijde instroom en uitstroom van materialen van het economische systeem analyseert en de economische en ecologische implicaties ervan. Er is echter nog steeds een gebrek aan begrip over hoe een wereldwijde transitie naar circulariteit eruit zou kunnen zien, en wat de omvang zou zijn van de potentiële economische, sociale en ecologische implicaties van circulair materiaalgebruik op macroschaal. Dit roept de volgende vragen op: is circulaire economie een manier om wereldwijd een economische en ecologische duurzaamheid te bereiken? En wat zijn de macro-economische, sociale en ecologische gevolgen van een overgang naar een circulaire economie?

Dit proefschrift, met als titel “Een beoordeling op macroniveau van circulair materiaalgebruik” heeft tot doel te beoordelen of circulariteitsinterventies kunnen bijdragen aan een duurzaam beheer van hulpbronnen, en te onderzoeken welke circulariteitsinterventies kunnen bijdragen aan een kosteneffectieve transitie naar een circulaire economie. Bij het beantwoorden van deze vragen wordt de milieukundige input-outputanalyse (EEIOA) gebruikt als methode om de economische en milieueffecten op macroniveau te beoordelen. In tegenstelling tot andere methoden (bijv. Levenscyclusanalyse (LCA) en materiaalstroomanalyse (MFA)), biedt de EEIOA-methode het voordeel dat de gehele omvang en structuur van de (nationale of globale) economie in beschouwing wordt genomen, zodat circulariteitsinterventies op een integrale manier kunnen worden geëvalueerd.

In dit geheel zijn de volgende elementen van belang. Ten eerste, hoewel EEIOA een geschikt kader biedt om circulair materiaalgebruik te beoordelen, is het belangrijk om te begrijpen hoe EEIOA kan worden toegepast bij de beoordeling van circulariteitsinterventies. Ten tweede is er een gebrek aan informatie welke materialen het meest van belang zijn in de omslag naar een circulaire economie. Ten derde is het nodig om de potentiële macro-economische, sociale en milieueffecten van een transitie naar circulair materiaalgebruik te bepalen. Tegen deze achtergrond behandelen hoofdstuk 2 tot en met 5 de volgende onderzoeksvragen (OV):

OV1. Wat is de stand van de techniek van milieukundige input-outputanalyse (EEIOA) bij de beoordeling van circulariteitsinterventies?

Om OV1 te beantwoorden, werd voor Hoofdstuk 2 een systematisch literatuuroverzicht gedaan dat zich richtte op EEIOA studies met als onderwerp circulair materiaalgebruik. Dit hoofdstuk analyseerde meer dan 90 publicaties die circulariteitsinterventies hebben beoordeeld. De publicaties werden geanalyseerd ten aanzien de mogelijkheden en beperkingen van het toepassen van de EEIOA-methode voor het doorrekenen van circulariteitsinterventies. Op basis van deze literatuur kon worden bepaald via welke archetypische benaderingen circulariteitsinterventies kunnen worden gemodelleerd met EEIOA. Ook liet Hoofdstuk 2 zien hoe elk type van circulariteitsinterventie zijn eigen benadering vergt ten aanzien van het aanpassen van intermediaire en finale vraag coëfficiënten, en het integreren van meer gedetailleerde data in input-output tabellen. Ook werd duidelijk dat een effectieve beoordeling van circulariteitsinterventies beter kan geschieden met fysieke input-output tabellen of hybride tabellen. Zulke hybride tabellen kunnen het gebruik van secondaire materialen en hergebruik van afval preciezer analyseren.

OV2. Hoeveel niet-teruggewonnen afval is er beschikbaar om in een bepaalde periode als secundair materiaal opnieuw in de wereldeconomie te worden ingezet?

Om de OV2 te beantwoorden, geeft Hoofdstuk 3 een schatting van de ‘circularity gap’ in 43 landen en 5 rest van de wereldregio's in 2011. De analyse is uitgevoerd met de hybride versie van de multi-regionale input output (MR-HIOT) database EXIOBASE. Dit hoofdstuk geeft ook een specifiekere definitie van de ‘circularity gap’. Eerst wordt gekeken naar totale uitstroom van materialen uit de economie: afval van productie en consumptie en afval dat vrijkomt uit het afdanken van in gebruik zijnde economische voorraden zoals woningen of infrastructuur. Het verschil met de hoeveelheid uitstroom die opnieuw in de economie wordt ingezet definieert het hoofdstuk als de circularity gap. . De wereldwijde instroom van materiaal bedroeg 77 Gt in 2011, bestaande uit materiaalwinning (74 Gt) en terugwinning van afval (3 Gt). Van de wereldwijde instroom van materiaal werd 40 Gt gebruikt voor energie- en voedseldoeleinden, 30 Gt werd toegevoegd aan de voorraden die in economisch gebruik zijn, en 7 Gt werd afval. De totale hoeveelheid afval inclusief materiaal uit afgedankte economische voorraden was 9 Gt in 2011. De ‘circularity gap’ bedroeg daarmee 6 Gt (d.w.z. totaal afval minus afvalterugwinning). Dit komt overeen met ongeveer 8% van de wereldwijde materiaalbehoefte in 2011. Op het niveau van landen en regio’s verschilt de circularity gap. Landen en regio’s met een hoog inkomen hebben per hoofd van de bevolking een hogere circularity gap als landen met een midden- en lager middeninkomen. Ook gaf hoofdstuk 3 aan hoe de circulariteitsinterventies die in hoofdstuk 2 worden beschreven, kunnen worden geïmplementeerd om de circularity gap van elk land en elke regio te verkleinen.

OV3. Waar in de wereldeconomie is het materiaal geaccumuleerd dat kan worden ingezet bij een circulaire transitie?

Hoofdstuk 4 maakt een schatting van de wereldwijde distributie van de hoeveelheid materiaal die wordt toegevoegd aan economische voorraden, zoals woningen of infrastructuur. Het hoofdstuk laat een verdeling zien per soort materiaal, economische sector en land of geografische regio, op basis van de MR-HIOT EXIOBASE. Zoals vermeld in hoofdstuk 3, bedroeg de hoeveelheid materiaal dat wereldwijd aan economische voorraden werd toegevoegd 30 Gt in 2011. Opkomende economieën en landen met hoge inkomens zijn goed voor circa

70% van de toevoeging aan economische voorraden in 2011. Deze landen zijn ook goed voor de hoogste toevoeging per hoofd van de bevolking. Uitgesplitst naar materiaalsoort gaat het grotendeels om niet-metaalhoudende mineralen (87,9%), naast ijzer/staal (5,2%), hout (4,5%), kunststoffen (0,7%), papier (0,6%), glas (0,5%), andere metalen (0,4 %) en textiel (0,2%). De bouwsector was verantwoordelijk voor een toevoeging aan de economische voorraden van 90% van de niet-metaalhoudende mineralen. Dit benadrukt het belang van het realiseren van circulariteit in de bouwsector. Hoofdstuk 4 gaf ook aan welke circulariteitsinterventies uit hoofdstuk 2 kunnen bijdragen aan het duurzaam beheer van materialen gebruikt in economische voorraden op de kortste en lange termijn.

OV4. Wat zijn de verwachte macro-economische, sociale en milieueffecten van circulariteitsinterventies op nationaal en mondiaal niveau?

Om OV4 te beantwoorden, gaf Hoofdstuk 5 het resultaat van een systematische meta-analyse van publicaties die wijzigingen in Bruto Binnenlands Product (BBP), werkgelegenheid en koolstofemissies als gevolg van het implementeren van circulariteitsinterventies analyseren. Deze literatuur omvatte meer dan 300 circulaire economie scenario's (CES) voor de periode van 2020 tot 2050. Deze scenario's werden geharmoniseerd zodat een statistische analyse uitgevoerd kon worden om te bepalen of circulariteitsinterventies zouden kunnen leiden tot een 'win-win-win'-situatie in termen van macro-economische-, sociale- , en milieueffecten. Op basis van de herziene CES's voor 2030 zouden circulariteitsinterventies kunnen leiden tot incrementele veranderingen in het BBP (mediaan (mdn) = 2,0%; interkwartielbereik (IQR) = [0,4-4,6]%) en banencreatie (mdn = 1,6%; IQR = [0,9–2,0]%), terwijl veranderingen in CO2-uitstoot substantieel zouden kunnen zijn (mdn = -24,6%), maar de waarden hebben een aanzienlijke spreiding (IQR = - [34,0–8,2]%). Hoofdstuk 5 besprak ook de 3 belangrijkste circulariteitsinterventies die in CES's werden gemodelleerd (met name belasting op grondstoffen, technologische veranderingen en veranderingen in consumptiepatronen). Ook besprak Hoofdstuk 5 de belangrijkste wijzigingen in modellen die gewenst zijn om zulke analyses nauwkeuriger te kunnen uitvoeren

In het algemeen lieten hoofdstuk 2 tot en met 5 zien dat circulair gebruik van materialen een belangrijke rol kan spelen bij het duurzaam beheer van natuurlijke hulpbronnen. Echter, een transitie naar een circulaire economie is niet voldoende om duurzaamheid te realiseren. Zo is de huidige hoeveelheid afval die beschikbaar is voor circulair gebruik niet voldoende om aan de vraag naar nieuwe goederen en diensten te voldoen. Dit komt doordat de wereldwijde materiaalbehoefte voor inzet in nieuwe economische voorraden (kapitaalgoederen) veel hoger is dan nu als reststromen vrijkomt uit de in gebruik zijnde voorraden kapitaalgoederen. Bovendien draagt circulair materiaalgebruik maar in beperkte mate bij aan het verminderen de behoefte van materialen voor voedings- en energiedoeleinden. Het betreft namelijk materiaalstromen die dissipatief worden gebruikt en niet in (vrijwel) oorspronkelijke vorm kunnen worden ingezet in de economie. Beleid ten aanzien van circulaire economie moet dus worden aangevuld met andere strategieën (zoals het uitfaseren van materialen voor energieopwekking via een energietransitie).

Dit proefschrift "Een beoordeling op macroniveau van circulair materiaalgebruik" draagt bij aan een beter begrip over de mogelijkheden en beperkingen van het toepassen van EEIOA bij het beoordelen van de implicaties van het implementeren van een circulariteitsinterventies. Het gebruik van de MR-HIOT EXIOBASE (in plaats van traditionele monetaire EE IOTs) bij zulke beoordelingen was een belangrijke stap voorwaarts. Een MR-HIOT voorkomt dat waardenketens in de economie in louter economische termen worden gevolgd, terwijl die vooral in het geval van afval- en reststoffen vaak niet representatief zijn voor fysieke volumes van materiaalstromen. Een voordeel van de EXIOBASE MR-HIOT is verder de hoge resolutie in economische sectoren en landen. Onderzoek naar circulair materiaalgebruik is gebaat bij het verder verbeteren van MR-HIOTs zoals EXIOBASE in termen van resolutie van sectoren en productstromen, de afvalfase, tijdreeksen, en de toevoegingen en onttrekkingen aan voorraden in economisch gebruik (b.v. kapitaalgoederen). Dit levert specifiekere informatie en inzichten op, waardoor beleidsmakers circulariteitsinterventies beter en effectiever zullen kunnen implementeren.

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To all of you, I just want to leave you with two words: *Pura Vida!*

Curriculum Vitae

Glenn was born on January 7th, 1988 in San Jose, Costa Rica. He grew up in the town of San Rafael, Heredia, where his passion for science grew up along with his hikes through tropical rainforests and coffee plantations. He was awarded with a sport scholarship from Saint John High School, where he graduated in 2005. Then, he was awarded with a sport and stimulus scholarship from the University of Costa Rica, where he obtained a Bachelor of Chemistry in 2011. By that time, he also collaborated as student assistant in several courses such as general physics, organic chemistry, and physical chemistry. After that, Glenn worked for 3 years as a researcher and production supervisor in Energias Biodegradables de Costa Rica S.A., where his research focused on biofuels production. In 2013, he received an Australian Award Scholarship to pursue his master’s studies at the University of Sydney, Australia. His graduation project was a collaboration between WWF-Australia and the Integrated Sustainability Analysis Centre from the University of Sydney, where he studied the impacts of international trades on biodiversity losses in Borneo. In 2016, he obtained a Master of Sustainability with distinction. Glenn moved back to Costa Rica, where he worked as a Research Associate at the School of Agricultural and Biosystems Engineering, at the University of Costa Rica. During this time, he developed bioenergy projects and courses for climate change mitigation and adaptation. At the end of 2016, he was selected as an Early-Stage Researcher in the Circuiet Marie Curie Innovative Training Network to start his PhD in the Institute of Environmental Sciences (CML) at Leiden University. Since then, Glenn’s research has been focused on understanding the potential implications of a circular economy on a global scale. His current works has been recognized by multiple organizations, for example, with a 2nd place prize of PRISMA-Award 2020 for ground-breaking research on sustainability assessment and policy, two nominations to the CML Stan Award as best PhD scientific article, and an article acknowledgement in Science for Environmental Policy of the European Commission's Environment Directorate.

Publications

Academic work:

- Aguilar-Hernandez GA, Rodrigues JFD, Tukker A (2020) *Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies*. Journal of Cleaner Production 278: 123421 https://doi.org/10.1016/j.jclepro.2020.123421
- Aguilar-Hernandez GA, Sigüenza-Sanchez CP, Donati F, Merciai S, Schmidt J, Rodrigues JFD, Tukker A (2019) *The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011*. Resource Conservation & Recycling 151: 1–9. https://doi.org/10.1016/j.resconrec.2019.104452
- Aguilar-Hernandez GA, Sigüenza-Sanchez CP, Donati F, Rodrigues JFD, Tukker A (2018) *Assessing circularity interventions : a review of EEIOA-based studies*. Journal Economic Structures 7: 1–24. https://doi.org/10.1186/s40008-018-0113-3
- Aguilar-Hernandez GA (2017) *Comprendiendo la sustentabilidad desde un punto de vista exergético en sistemas adaptivos complejos*. Ingeniería 27. DOI 10.15517/JTE.V27I1.25524
- Aguilar-Hernandez GA, Deetman S, Rodrigues JFD, Tukker A (submitted) *Global distribution of material inflows to in-use stocks in 2011 and its implications for a circularity transition*. Journal of Industrial Ecology
- Donati F, Aguilar-Hernandez GA, Sigüenza-Sanchez CP, de Koning A, Rodrigues JFD, Tukker A (2019) *Modeling the Circular Economy in Environmentally Extended Input-Output Tables: methods, software and case study*. Resource Conservation & Recycling 152: 104508. https://doi.org/10.1016/j.resconrec.2019.104508

- Sigüenza-Sanchez CP, Aguilar-Hernandez GA, Steubing B, Tukker A (2020) *The Environmental and Material Implications of Circular Transitions: A Diffusion and Product Life Cycle-Based Method and Framework*. Journal of Industrial Ecology: 1–17. https://doi.org/10.1111/jiec.13072

Codes and data repositories:

- Aguilar-Hernandez GA (2020) *Supporting Information of "Global distribution of material inflows to capital formation and its implications for a circularity transition"*. DOI: 10.5281/zenodo.3894238
- Aguilar-Hernandez GA (2020) *Supplementary Material of "Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies"*. DOI: 10.5281/zenodo.3820181
- Aguilar-Hernandez GA (2019) *Supplementary Material of "The circularity gap of nations: A multiregional analysis of waste generation, recovery, and stock depletion in 2011"*. DOI: 10.5281/zenodo.3245310