A macro level of assessment of material circularity
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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).

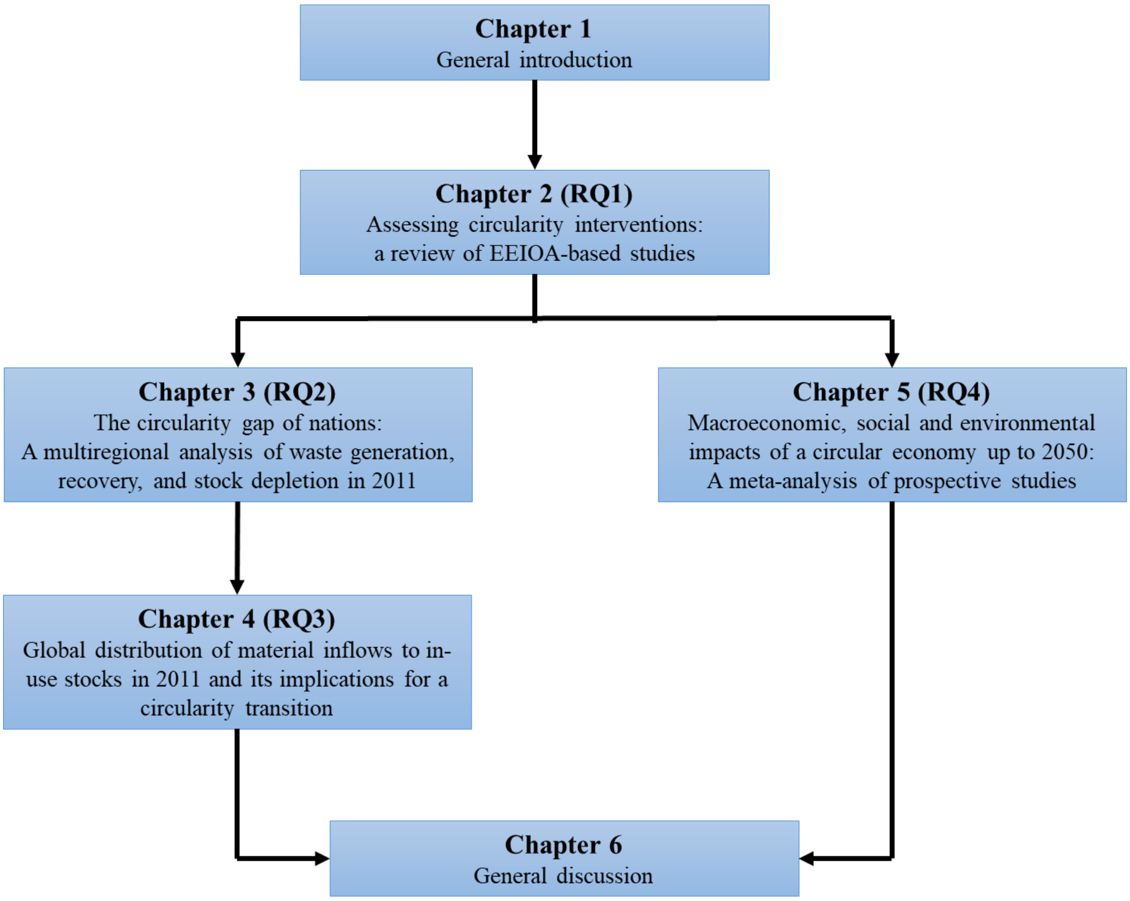

Figure 1.1. Outline of this dissertation linked to each research question (RQ)

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.

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