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Material Circularity and its Socio-economic Values

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Introduction to the thesis

The presentation of this thesis might as well take inspiration from a political economy lecture. The professor could start referring to the nature of our research object, our "*τι εστι*". All economics sciences sisters study a branch of human choice in bounded immaterial space. Compared to other sciences, Thomas Carlyle defined it as dismal. Environmental economics is among its sisters the most dismal one. It deals with material scarcity and the difficulty of finding a straightforward solution to current and future problems. A topical reference is a work of Malthus around population law (Malthus, 1798). According to the author, population growth is doomed to be tapered by nature limits via war and famine. His work's argument assumed that population growth was linear to time while land returns grew only logarithmically. Fortunately, technological advances debunk this theory. History has some difficulty finding clear examples for the 'Malthusian trap' (Diamond, 2011). The definition of general laws that interlink human activity and natural laws is the available frame within which we find environmental economics studies. Therefore, we are interested in studying these laws is not mere curiosity or base research.

Environmental economics models and their applications are relevant for policy making, market indicators, and risk assessment. However, I believe some caveat principles are inescapable when entering this field. We can relate to pre-cognitive classification to define the sphere of action and assign values according to any objectives. An example of this classification is the setting of preferences within the Arrow impossibility theorem; why do we prefer something instead of another? In some sense, we could say environmental economics has a constrained vision over human action implicitly. This definition was firstly introduced by Schumpeter (1954) as the set of logical but precognitive causal relations that describe a scientific or political thought. It has been classified then by Sowell (2007) as a compass to interpret possible outcomes and limitations of studies and rational thoughts. According to the author, there can be a spectrum of visions between a pure unconstrained vision and a constrained one. The differences arise according to human nature, solutions to problems, and free will. Both visions characterize environmental economics works. In this thesis, the constrained vision will be the most relevant. I refer to two main points. Sowell represents one and the work against the "anointed" vision (Lomborg, 2018; Sowell, 2019). The other foremost exponents of environmental economics vision are represented by Ayres and Meadows' works (Ayres, 1995, 2019; Ayres & Van Den Bergh, 2005; D. Meadows et al., 2004; D. H. Meadows et al., 2018). Among these, we find Bubble economy and Limits to growth.

Material limits and trade-offs between solutions define the constraints that bind our choices. This premise requires thinking outside the perfect dynamics of marginal utility in the first class of public economy. A particular case of the field of studies is presented by ecological economics, where the focus lies in defining the benefits of non-marketed commodities. Constrained vision carries implicit pessimism and caution in elaborating a narrative. For instance, one topical moment was the Nobel Prize to Nordhaus. No matter the stand an environmental researcher takes, its work is a distinction for economics' vision. Authors with a constrained vision criticized the uncertainty and the presumed perfect transformation of production inputs, such as energy.

A constraint vision of environmental economics stands on two primary principles. The first is the precautionary principle or *Vorsorgenprinzip* for a "proactive" approach (O'Riordan, 2013). According to this principle, uncertainty is implicitly damaging, and therefore balancing actions have to be taken. The other relates to the implicit incomparability between capital and energy. Economic capital is enumerated in monetary units and dissipates slowly due to human imperfection. Stock is enumerated as the economic value of material assets too. Mass does not dissipate as energy and could be treated as capital. Economic models usually treat capital and material stock as univocally defined. Stock is accumulated according to some input-output mechanisms, with no intrinsic loss. The actor that portrays these flows is usually perfectly rational, and productivity is defined by exogenously evolving technology. This dynamic has been called Circular Economy (Turner & Pearce, 1990). Rising interest toward the potential benefit of material cycle optimization has fragmented definition into an umbrella of many others (Homrich et al., 2018). In this collection of works, the definition that describes the research object is material circularity (Zotti & Bigano, 2019). Matter satisfies technological purposes and is cumulated, consumed, or transformed. In this sense, confusion of definition compelled researchers to frame Circular Economy under an umbrella of definitions. For instance, the policy framework to reduce the amount of useless or even dangerous material flows is also considered "Circular Economy". There is no reason to think these two definitions are disentangled.

Material control requires acknowledging the presence of flows and their determinants. It arises a nexus between the utilitaristic objective of policymaking and material flows. The space in which a "social planner" intervenes is where the society elaborates such flows. Industrial ecology identifies this space as the Anthroposphere. Edward Suess (Suess, 1875) defines the portion of the natural environment that is modified to constitute human habitat. Therefore, it encompasses immobile components (such as fabric structures, fields devolved to agriculture, cities) and a mobile component (commodities, vectors of air, land, and water). This space interacts with the geosphere for resources and waste. In the so-called framework of the linear economy, the geosphere is simply a sink and origin of resources. In a circular economic model, the sink is often a reservoir of materials. The expected result is, therefore, a reduction of impact on the natural environment. The correct estimation of benefits and adverse effects requires the knowledge of flow composition, dynamics, and relation to anthropogenic activity. No matter how we try to change perspective, any mass or material stock is necessarily related to energy consumption. It can be traced in production, transport, or waste management. The capacity to consume and then discard waste describes utility and accumulation. But this stock is not uniform either its sub-components: they vary according to utility feedbacks.

Intrinsic material variables such as timespan (for durable goods) are usually all collected in capital depreciation. According to the accumulation state, the subsystems adapt due interest of individuals varying accordingly. Despite all possible technologies to recovery or efficiency improvement, some matter is cumulated in some form of useless stock: accumulation is what some may call entropic change. It is an unavoidable aspect that, in many cases, has been misinterpreted (Kovalev, 2016b). Despite its constant and inevitable growth, the circular economic vision attempts to reduce it. But to do so, material circularity must be studied.

The geopolitical framework we focused on was European Union. The availability of data and political interest towards material circularity makes the conglomerate of nations perfect. The application of circularity and the artificial reservoir is made on Electrical and Electronic Equipment. This category of commodities contemplates all products which functionalities are accessed with electricity. A more detailed description will be made in chapters four and five. Their relevance is their impact on the standard of living, digitalization, and, finally, richness in critical raw materials. With the introduction of extended responsibility, manufacturers of electrical equipment must consider both a safe supply chain and material accumulation. We cannot have a different phone, computer, or fridge every year despite the interesting novelties in discursive terms. A sustainable and circular world is partly bound to frugality. If waste has to be reduced and natural resources spared, we have to find models and approaches to deal with the optimal pathways for transition. During this thesis, two fields of studies different from economics allowed me to use material circularities to infer their socio-economic values.

Social Ecology and Environmental Economics

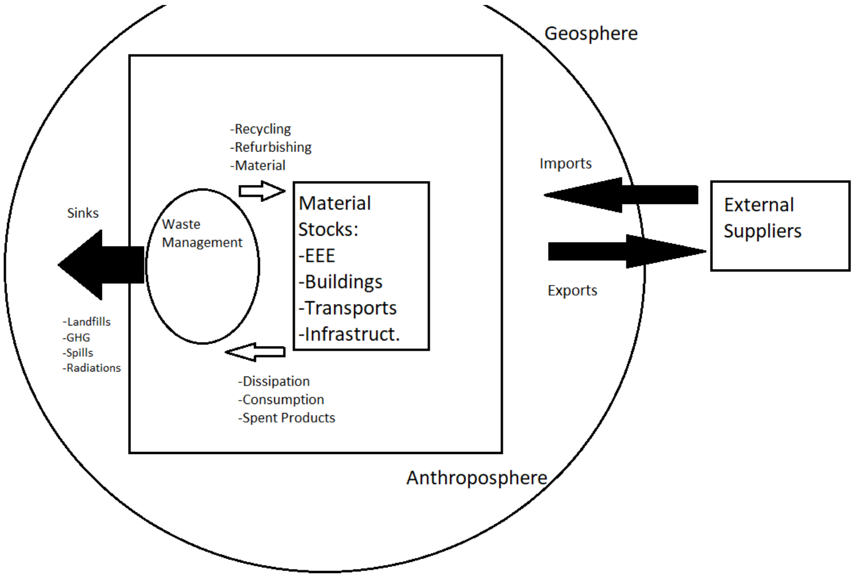

Figure 1: Interactions of the Anthroposphere/Technosphere

To understand the mechanisms that influence material accumulation, disposal and to frame the impact of mineral governance, we tried to understand the potential links between three main literature fields. The vision that guides our study is circularity under the definition of environmental economics.

However, the description of flows and the evaluation of responsible trade flows stemmed from Social Ecology and Political ecology. According to Vienna School's works, the core axiom of social ecology is the coevolution of anthropic and natural systems: they influence each other over time in a co-causality relation (H Haberl et al., 2016). The resulting link is evident in material transformation and organization and innovations in our societies (see, for instance, biomimicry and eco-friendly architecture). According to Social Ecology, the primary process of appropriating resources is called “colonization”: these are those activities that deliberately alter natural systems to render them more useful for society (Fischer-Kowalski & Haberl, 1998). It can have object natural reservoirs, renewables, and non-renewables. Transition to a circular economic model must consider the diversion of such colonization from the geosphere into the Anthroposphere; unless we intend to disrupt the economic systems called by some de-growth (Kallis, 2011). The data on waste management, material accumulation made by the project ProSum for Electrical and Electronic Equipment was based on an inflow driven analysis, a methodology coming from social ecology.

Our interest is mainly related to literature related to socio-environmental and economic fields with mineral and manufactured commodities known as Electrical and Electronic Equipment. This difference allows us to focus on certain aspects of the Anthroposphere, policies, and material circularity. While this thesis aims to produce environmental economics research, the other two fields represented a relevant source of data and perspective. The generation of data regarding human rights, material accumulation, and others originated from political ecology and social ecology. The accounting principles are therefore coming from different approaches of study. We related the definitions for our purposes. In some sense, the theoretical premise and research questions are mainly derived from reading journals and works primarily done by economists. However, the techno-sphere interactions within a circular framework required the contamination with other fields’ results and approaches. For instance, the idea that human society colonizes the natural world to satisfy its needs comes from Social ecology. The structure of the Anthroposphere influenced by this field could be summarized by figure 1. Each nation has artificially recognized boundaries and natural ones with its geosphere. The borders’ purpose is to allow differentiation of resources between the internal ones and the external ones. The natural boundaries, however, are represented by the geosphere and the Anthroposphere. Societies extract virgin materials. The political disparities of mineral acquisition are studied, however, by Political ecology.

Political ecology is the study of struggles deriving from the material acquisition. It has been partly influenced by Ecologic structuralism and neo-Malthusian studies (Bassett & Peimer, 2015). While the ideological premises are not interesting for research purposes or policy ones, the identification of problematics is geographically broad, thanks to the field's development far from European shores; in the second and third world (Robbins, 2002). Since the seventies, this local presence in developing countries for several decades allowed the proliferation of ecological activisms. The results are a granular reporting system that EJAtlas is the synthetic proof (Temper et al., 2015). European Union has a particular interest in controlling the quality of the mineral supply chain. We dedicated a summary of policy objectives and instruments determined by the European Union's legislative acts to foster the transition to a more Circular Economy.

Policy framework: the European Material Governance

The control of material flows and waste reduction is one of the core objectives of the European Union. To achieve such a goal, it has used several instruments. Among these, we find Communications, Regulations, and Directives. The general purpose was to reduce the number of side-products of economic activities, mitigate supply risk and increase the internal production strength. It is not the purpose of this work to study the aspects linked to mining production. International trade and recycling policies are relevant for this work. For instance, the structural break registered in waste management/material accumulation in 2008 is primarily driven by regulation: the European Commission presented the Waste Framework Directive, affecting waste management and waste prevention guidelines. Since national legislative systems must abide by European acts, national level and all sub-national levels political and socio-economic systems shifted their governance according to such changes (not with the same speed). The use of Communications does not generate obligations to state members nor other organizations. It points at the relevant indicators to evaluate the targets determined by regulations or, more importantly, Directives. Setting general targets or criteria is the primary objective for Directives.

Material circularity and its socio-economic effects are affected by the so-called “Policy and strategy for raw materials”. According to the “Raw Material Initiative” (Commission of the European Communities, 2008), the welfare generated to over 30 million workers relies on strategic materials' availability. Therefore, the effective control of the supply chain is crucial for economic growth and sustainable development. A response to this came from European Union. Its Institutions established a long-term strategy to tackle risks coming from outside the common market and within. The core strategy to supply in long-term European markets relies on three pillars:

1. Fair and sustainable supply from international markets
2. Sustainable supply of raw materials from within the European Union
3. Resource efficiency and supply of secondary raw materials through recycling

In this work, we will focus on points 1 and 3. We collected in table 1 the policy instruments that European Union used to pursue the strategy. While the set does not represent the whole legislative system, we frequently encounter these during the research. Taking a first look at the Mineral governance, we see that the strategy implemented studies to inform practitioners of the most endangered materials according to economic importance, supply safety, and human rights violations. The interest toward such groups rose between 2011 and 2012. In those years, Chinese authorities unilaterally restricted exports of Rare Earth elements, actions that were sanctioned to be illegal by the World Trade Organization.

While the response of European authorities was steady, it happened in years of global uncertainty. The introduction of Basel III after the international crisis indicated that markets were not capable of adjusting automatically. With the intervention of actors capable of exploiting market power for political reasons, international treaties outside the OECD and the EU were insufficient for sustainable goals. Thus, the public intervention was required. The first step taken was to develop a list of critical raw materials in 2011. Due to other conflicts in the raw material sectors (Cobalt in Congo and Lithium in Bolivia), the list was repeatedly renewed. These communications identified which minerals had to be considered in strategic flows and which aspects constituted criticalities.

The identifications of such materials were intended to raise the focus over the supply chain of specific sectors. Conflicts and application of illegal national policies could induce severe limitations in technological sectors' economic performance and green innovation. European institutions and practitioners' main objective was to acquire as much information as possible regarding critical raw materials origin and suppliers. The Due diligence regulation requires industries to report vulnerability sources from CRM suppliers since January 2021.

Regarding Circularity, waste, and resource efficiency, three primary directives affected this thesis's research issues. The most important is the Waste Framework Directive of 2008. It set the definitions related to waste management such as waste, recycling, recovery. It explains when waste ceases to be such and becomes a secondary raw material (so-called end-of-waste criteria) and distinguishes between waste and by-products. Furthermore, the Directive introduced two principles regarding waste management: the "polluter pays principle" and the "extended producer responsibility". Includes two new recycling and recovery targets to be achieved by 2020: 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households, and 70% qualifying for re-use, recycling, and another recovery of construction and demolition waste. The Directive requires that the Member States adopt waste management plans and waste prevention programs. Regarding our work, this directive constituted a structural break in waste generation as well recovery. Since waste was reduced, we demonstrated that material stock increased due to its enforcement in the last chapter.

Our study necessarily uses and cites the regulation of 2017 and communication of 2018 regarding WEEE flows and EEE stock. The definition of stock and waste flows is determined along with this legislative *corpus*. Within the chapters, the intervention of the EU has been to affect the structure of circularity. After this presentation, we will briefly illustrate the design of the thesis.

Table 1: Summary of legislations

Issue	Policy	Citation	Type	Objectives	Year of Implementation
Mineral Governance	Due diligence regulation	(European Parliament and Council, 2017)	Regulation	-laying down supply chain Due Diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas	2017
	1st CRM list	(European Commission, 2011)	Communication	Identification of 14 critical raw materials	2011
	2nd CRM list	(European Commission, 2014)	Communication	Identification of 20 critical materials	2014
	3rd CRM list	(European Commission, 2017b)	Communication	Identification of 27 critical materials	2017
	4th CRM list	(European Commission, 2020a)	Communication	Identification of 30 critical materials	2020
Waste and Circularity	Waste Framework Directive	(European Parliament and Council, 2008)	Directive	-Introduction of principles -targets: by 2020, 50% waste separation Households, 70% construction	2008
	Waste from Electrical and Electronic Equipment	(European Commission, 2017a)	Regulation	-Introduction of WEEE indicators and weight measuring -controlling the flows and report	2017
	A monitoring framework for the Circular Economy	(European Commission, 2018)	Communication	-Determination of the major indicators for measuring circularity	2018

Structure of the thesis

This work is structured in five chapters. The first two chapters are related to the European Mineral Governance, while Circularity and Waste are tackled in the last three. In the first chapter, we presented the inverse correlation between the objective of safe supply and circularity. While certain materials showed potentials for recovery, others resembled safe supplies. According to the flow analysis we provided, several materials supply chains were neither sufficiently recyclable nor unrelated to human rights violations. In the second chapter, we presented a deeper look at the trade networks. Using data on human rights violations, we differentiated each trade node according to the severity of past human rights violations. The novelty introduced to scientific literature represents a commented set of maps regarding all critical raw materials.

The third chapter analyzed the Environmental Kuznets Curve Hypothesis's methodological limitations regarding municipal waste and its separated components. The study implicated that there should be a quantifiable relation between economic activity and waste generation. Therefore, it should be possible to infer some connection with the subcomponents of waste too. However, the results showed that such relation is not constant along with economic growth and varies across provinces in Italy. Furthermore, the spatial approach we employed identified spatial interactions between provinces; this indicated spillovers in waste collection performances.

The fourth chapter used stock and waste data from 1980 to 2020 to estimate the maximum potential recovery from EEE. The estimate proved that this rate is varying due to the changes in the in-use stock composition. We studied the same data in chapter five, which are the driver of EEE stock accumulation. We employed drivers suggested by previous studies such as Economic activity, population characteristics, and average product timespan indicators for the analysis. As indicated by the European Union communication of 2018 on circularity, we added a theoretical premise to the impact that circular innovation has on stock accumulation. The results underlined how this particular form of innovation foster greater material accumulation.

Chapter 1
Circularity and Safety of Raw Material Imports

Abstract

The development of next-generation technologies requires a set of critical raw materials (CRM). Energy accumulators and electronic devices all contain a certain amount of these. Such elements' versatility and utility come together with the limited number of countries where their extraction and production occur. As these materials' demand is growing globally, main concerns arise concerning the global supply chain's security. Several works highlighted the risks associated with these materials without presenting clear interaction between such factors. In this chapter, a classification of the three aspects is presented. The approach will contain the presentation of the main characteristics of recyclability and institutional status of exporters. A synthetic index is derived and plotted against the potential of recycling per material. In such a manner, we can group minerals according to sourcing vulnerability: one is coming from material recovery and the other via imports. According to our findings, Electrical Vehicles carry the highest exposure for their main components in circularity and human right violations. Ending remarks highlighted the limitations of our research, where possible interest for future research may lay.

Abbreviations: Critical Raw Materials (CRMs), Electrical and Electronic Equipment (EEE), end-of-life recycling input rates (EOL-RIR), European Union (EU), Electrical Vehicles (EV), Heavy Rare Earth Elements (HREE), light rare earth elements (LREE), Responsible Sourcing (RS)

Introduction

Acquisition of Critical Raw Materials (CRMs) is topical European Union (EU) strategic Agenda. The institutions established a three-fold policy direction to aid in this context. It involves safe mining within the EU economic area, waste recovery, and responsible sourcing. In terms of policy setting, the first relates to sustainable use and new explorations (Hamor, 2004; Vrkljan et al., 2017). We recall material recovery from municipal waste from the Circular Economy context as urban mining (Cossu & Williams, 2015). Households' waste is not the primary source of waste within the EU economy; however, it represents one of the core issues of EU waste policy (Expósito & Velasco, 2018). Finally, Responsible sourcing (RS) practices are intended to reduce the security stress from imports. According to RS's principles, private and public organizations weigh suppliers according to local communities' relations (van den Brink et al., 2019). Due to industrial dependency, CRM is often extracted from nations that disregard human rights: the reason why some of them are part of the so-called conflict minerals (Koch & Burlyuk, 2020). The policy issue abides by the OECD Due Diligence practices (OECD, 2016a). While internal EU production increases the safety of the supply line, the other two are face limitations. Material recovery from waste still faces technological uncertainties (Ali et al., 2017), and harmonization of Due Diligence data is still in evolution (OECD, 2020). Among its requirement, we find robust company management systems; identify and assess risk in the supply chain; design and implement a strategy to respond to identified risks; carry out an independent third-party audit of supply chain Due Diligence; report yearly on supply chain Due Diligence. This effort is needed as Mineral Governance and policymaking at different levels have the capacity to anticipate supply risk and political crises to anticipate risks and crises (Bleischwitz, 2020; Bleischwitz & Bahn-Walkowiak, 2007).

Great effort has been made to address the economic criticality of CRM within the EU and in other countries. Several studies have explored the limitations in circular technology and supply chain security. Fewer have inquired about the relation between criticality issues. We will ask about the critical link between RS and the circularity of CRM. The increased interest towards Transition to a low-carbon society binds industrial production to sustainable objectives. Therefore, we will apply this analysis for four commodities groups relevant for this purpose: Electrical and Electronic Equipment (EEE), electrical Vehicles (EV), Solar panels, and wind farms. The indicator of RS is calibrated according to market concentration and national institutional quality. We will use recycled materials to raw materials demand for circularity, known as the end-of-life recycling input rates (EOL-RIR). This is not the only possible indicator of circularity. It is, however, the one adopted by the EU commission and EUROSTAT to classify materials for circularity (Talens Peiró et al., 2018). The criticality analysis will involve the definition of a matrix of risk indicators. The criticality measure involves a Cartesian distance method: a detailed explanation will follow in the methodology section.

EU policies around material security started around 2008 with the “Raw Material Initiative”: a set of critical elements for EU industries were identified. A revision of the criticality definition was implemented several times. The first official publication was in 2011 with 14 CRMs. Following editions every three years increased the number of elements: 2014 with 20, 2017 with 27, and 2020 with 30. Such surge could be interpreted by the attention that the EU commission had towards several evolving topics. Circular Economy policy packages were implemented during those years: 2008 and 2014, the Waste Framework Directive, Circular Economy Action Plan in 2015 and 2017 were the waste of the EEE package. The Paris Agreement signatures accelerated climate Change policy in 2016.

Regarding Responsible sourcing, the EU passed the EU’s Regulation on Responsible Sourcing of Minerals, also sometimes referred to as the 'Conflict minerals Regulation', in May 2017. According to this legislation, by January 2021, around 95% of CRM imports should follow RS criteria (EU, 2017). The recommendations declined within the Due Diligence Guidelines follow the premise of corruption avoidance, human and environmental rights, conflict avoidance (OECD, 2016b).

The article is structured in such a manner. The literature review presents the major works regarding CRM criticality. The methodology section is used to explain the derivation and use of indicators for our analysis. The Results section will show a synthetic outcome. In the discussion, we will comment on the relevance of the results according to each sector and how this could affect the EU agenda's outcome. Finally, a review of the limitations of our methodology is presented along with the possible new application.

Literature

The thriving market for consumer and portable electronics and low-carbon technologies (hybrid and electric vehicles, wind turbines, and solar panels) is heavily dependent on the availability of critical raw materials (CRMs): it is possible to find studies on EV (Jones et al., 2020), solar panels and wind farms (Rabe et al., 2017). Their extraction, production, and trade are associated with various risk factors. In 2013, a study conducted by the IISD identified 32 materials as being significant for the de-carbonization of the European energy system (Church & Crawford, 2018). Some of them are classified as "critical" and included in the EU critical raw material list being either scarce or extracted in a limited number of countries (Blagoeva et al., 2016). Commonly, criticality assessments consider the 'supply risk' and 'economic importance' of the raw material. Supply risk reflects the severity of the impact on the disruption of supply chains and is based on the concentration of major suppliers and their political stability. Economic importance reflects the sum of end-use sectors' value that consumes raw material (Song et al., 2019a). Other studies also include analyses of the reserves and the number of raw materials. Some have been confirmed and can be economically recovered with currently available technology, even by EEE waste (Mazzarano, 2020). It is possible to estimate depletion rates for global reserves with a long-time focus. In general sourcing material use from production, chains relate equivalent measures (Pehlken et al., 2017; Ziemann et al., 2018). Such approaches are similar to ecological footprint, applying water and carbon emissions (Misopoulos et al., 2020; Stefanakis, 2019).

Criticality assessment usually involved the development of indexes. One of the most famous has been annually derived from UK geological survey (British Geological Survey, 2015). It uses a composition of several indicators involving geopolitical risk, economic relevance, recycling potential, and ore scarcity. However, several of such indicators have been subjected to criticism in the context of life-cycle assessment (Cimprich et al., 2019) in the sense that they made indicators challenging to use in supply chain analysis. The geopolitical risk component is somewhat relevant in CRM studies, but it is significantly mitigated by recycling capacity, becoming a less critical factor (Santillán-Saldivar et al., 2021).

Furthermore, scales and non-continuous indicators are not valuable for capture correlations in the supply risk index used in criticality indicators (Blengini et al., 2017). From the Markowitz portfolio approach, the correlation between indicators is a possible tool to minimize risk. For CRM, there is no significant correlation between depletion, self-sufficiency, and economic importance indicators (F. F. Martins & Castro, 2020). Economic importance has also been uncorrelated to supply risk (Arendt et al., 2020).

The study of indicators correlation is a recent development, and RS aspects are often not considered a primary interest. Furthermore, the result in terms of which material is more critical is a redundant exercise. Top positions are often occupied by the same materials (Martins & Castro, 2019). There are comprehensive studies on the supply chain of CRMs, Lithium, and Cobalt, for the European Union

(Deloitte, 2015) and criticality assessments about reliance on imports and macro-economic factors. Few studies pay attention to the correlation between the institutional quality of exporters and material circularity. The instability of institutional systems affects the endurance of economic relations. This generates uncertainty and impacts products' value-chain (Ambekar et al., 2019; Silva & Schaltegger, 2019). There is no absolute way to examine stability. According to a normalized scale, available indexes are based on experts panel and grade nations (KUNČIČ, 2014). This indicator has been used in several studies of CRM supply risk. The following section will show how it is possible to correlate market safety to circularity in the next section.

Methodology

To evaluate materials' criticality under the frame of circularity vs. market safety, we employed three indicators. For circularity, we adopted the percentage of reuse of discarded materials, the EOL-RIR. Volumes of CRM international transactions could be traced to the exporters using the COMTRADE dataset. We use the reference value of 2018, as it is its latest entry. According to each product, this trading indicator is hereby used to derive each exporter's market quota. Institutional quality is based on six normalized indicators. The EOL-RIR was found to be the most suitable circularity indicator in criticality analysis. It aligns well with EU targets, including raw materials policy, and the section explains how it can be calculated using Material System Analysis data (Talens Peiró et al., 2018). EOL-RIR refers only to available recycling. It is the percentage of participation of discarded materials in input to production. CRM is defined by both market concentration and a north-south dynamic of human rights. Since institutional quality does not directly identify human rights violations, we assumed that institutional quality is a robust protection measure. Thus, we do not presume that nations with generally good institutions have no infringement. Human rights could be violated everywhere, but good institutions tend to repair or counter the damage.

Raw materials exporters with stable institutions might host relatively decent work environments. When rights are violated, it is more probable to restore the previous situation than in a nation with weak or unstable institutions. The operational definition of institutional quality is based upon a rating approach. Estimating a general value of quality is non-trivial. According to Regulatory quality, six indexes of quality evaluate nations, Government effectiveness, the rule of law, Corruption, Voice, and accountability index. Values of such variables are collected in indicators of Worldwide Governance Indicators. They are estimated using the unobserved components model. The premise underlying this statistical approach is straightforward – each of the individual data sources provides an imperfect signal of some more profound underlying notion of governance that is difficult to observe directly (Kaufmann et al., 2011). The distribution of such indexes is normal and always has a variance of 1 and a mean of 0, with a minimum value of -2.5 and a maximum of 2.5. Since we cannot choose which the more effective in preventing is or restore human rights, we will assume that they are jointly and equally responsible for human rights respect. Since it is needed positive values from a normal distribution, the exponential value will be used in such way:

$$I_i = \sum_{\forall m} e^{-xm} \tag{1}$$

The generalized index “I” for a country “i” is the inverted average between the six indexes' value. Each index ‘m’ could be given any weight ‘x’ according to institutional quality the criticality assessment requires. However, as previously stated, it might be better to have no discrimination on such occasions. Here all weights are equal to 1/6. This methodology is helpful as it does not substantially change the value of distributions' variance, avoiding other biases to our analysis. Since we had to refer the matter to a material, we matched the generalized index with the market participation.

$$M_k = \frac{1}{n} \sum_{\forall i} p_i I_i \tag{2}$$

In such a way, the index of market institutional quality “M” for material “k” is an average of nations' institutional quality. The value can vary from 0 to 100. The meaning of the index is a positive interaction between a market distribution and the quality of partners. The maximum level of the index can only be achieved when the market is split between fair exporters: the lower the level, the more concentrated the market around unfair partners. Since market distribution is not normally distributed, we cannot expect the “M” index to appreciate the same properties as institutional ones.

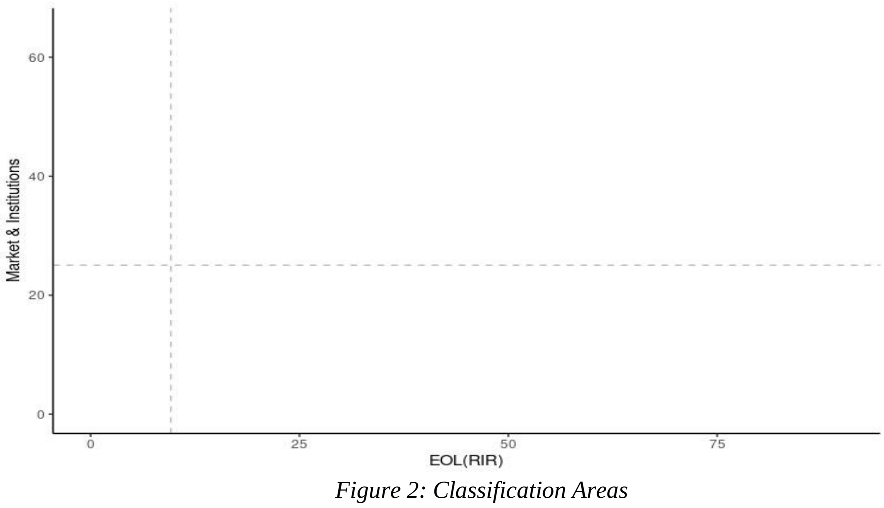

Figure 2: Classification Areas

According to circularity and market source vulnerability, the classification of materials will be plotted on a reference of two axes. The x-axis will represent the first while the y-axis the latter. Splitting the area into four, it is possible to discern between zones of no policies (both high values), overall criticality (low and low), high market vulnerability, and low circularity. It is possible to see the objectives according to frequencies. The areas will be split according to the median value. As reported in figure 1, half of all materials have either very low EOL-RIR (˜8) or common market vulnerability (˜22). Each commodity is constituted by a cloud of points spread between four areas. According to where these dots are located, it is possible to see where each sector should focus its policy.

CRM in international trade datasets condensates small flows into groups of transactions, with the case of Heavy and Light Rare Earth Elements (HREE and LREE). The former comprehends Yttrium (Y), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu). The latter comprehends Scandium (Sc), Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu). Furthermore, Group 5 elements have to be considered as a whole. This collects Vanadium (V), Niobium (Nb), Tantalum (Ta), and Dubnium (Db). Criticality assessment considers, therefore, 28 materials and groups.

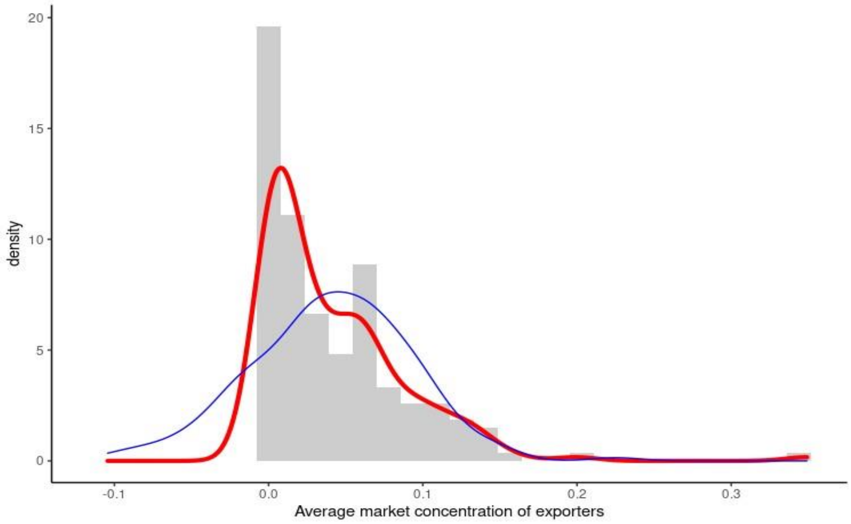

Figure 3: Market concentration per exporters, S_i

Market concentration could be considered on two levels. One could be captured by index M as the proportion of trade that each nation control for a particular CRM. The second appears when nations participate and possibly control several markets. To summarize market concentration Shannon index of concentration is applied. Its derivation originates from communication theory but has found prolific social sciences application (Tabner, 2007). The lowest value of 0 indicates the monopoly of markets of one country on every market. The number of exporting counties is collected in i = 1,..., N, and commodities in k = 1,..., K

$$S_i = \frac{1}{K}\sum_{\forall k}\sum_{\forall i} p_i \, ln(p_i) \tag{3}$$

We suggested in figure 2 that the number of dominators is few in CRM markets. This means that while if these nations both have unstable institutions and deal with low circular materials, it is rather difficult to address diversification. For our purpose, the M index is penalized by high concentration for commodities exchanged in this condition, even by very stable countries. Using a normal distribution fitting (blue), it is possible to compare this panel concentration to a"normal one". In figure 2, a comparison of concentration is highlighted. Dominant exporters do the most transactions of CRM. The normal distribution in blue is centered on S_i mean and standard deviation.

The M index multiplies market concentration to the "I" index of institutional quality. This index has low tails, and most firms are distributed around its mean of 6. Nations with an index around 1 have the most inferior instability to report, with all indexes near -2.5. The characteristics of such distribution are helpful in penalize extreme events and allow higher points in middle-tier countries. The interaction between such data is reported in the result section. To have a comparable index of criticality, we needed to synthesize the correlation between the indicators and the distance to the most unsafe of trades for RS-circularity objective: those low on both M and EOL-RIR (c in equation 4). Since we intend to address the trade-off's usefulness, we place no preference between the two indicators. Cartesian distance between each element (0,0) functions as a Pareto-efficient indicator: materials are given a higher value if there is any form of hedging strategy between circularity or safe markets.

$$D_k = \sqrt{M_k^2 + c_k^2} \tag{4}$$

According to EU standards, the analysis we provided allows for interpreting market safety results according to possible RS considerations and circularity. We reported with this the outcome of our study.

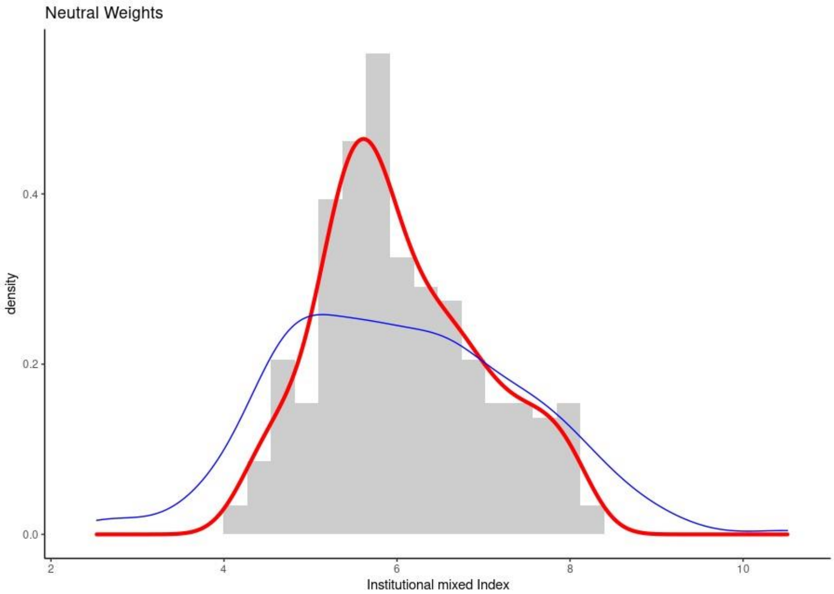

Figure 4: I index with normal density fitting.

Results

We reported a summary of the preliminary analysis in table1. Among essential CRM categories, it is possible to find LREE, HREE, and G5. Their market is respectively controlled by Japan (15.44%), the Popular Republic of China (11.6%), and Brazil (24%). Cobalt, LREE, and Silicates are the lowest in terms of circularity, with application in EV, EEE wind, and solar farms. For market and institutional fragility, Molybdenum and Cobalt are the lowest. The latter is particularly vulnerable for both factors.

China represents the most relevant source of market concentration and instability. While it is ranked low on all institutional quality indicators, it is the dominant player in several markets. Among these, we find Bismuth, HREE, Molybdenum, and Nickel. Cerium and LREE are dominated by Japan, which generally accounts for stable institutions.

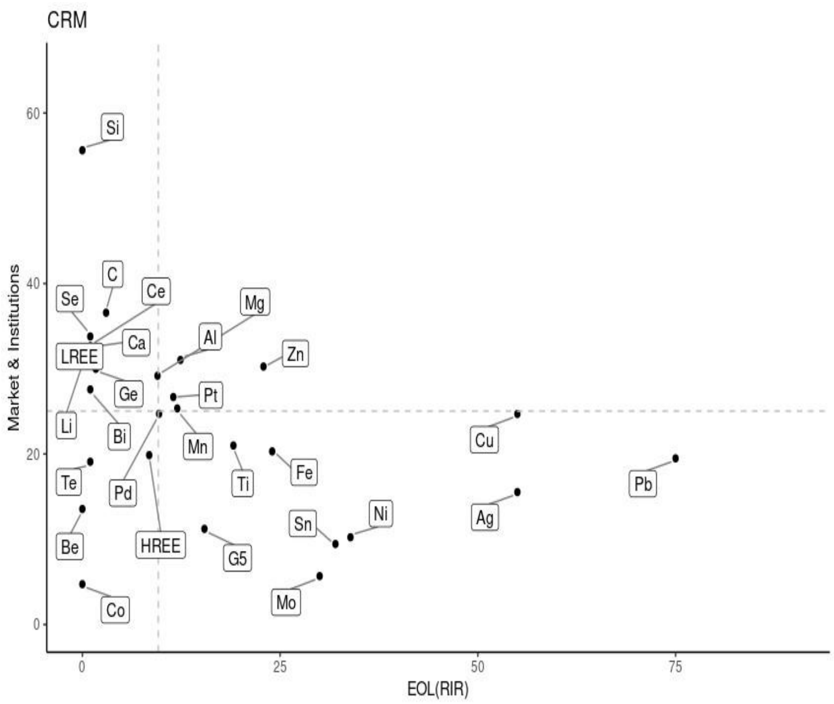

Figure 5: Scatter plot with the indication with areas

In responsible sourcing, "top-down" approaches based on institutional indicators for critical analysis have generally similar results, despite different focus. In our case, we developed a method based on three major indicators: market safety, circularity, and their Cartesian distance index. Institutional quality has been weighted to market participation. In case most any market is composed mainly by overall fragile states, we called the market tainted. The comparison element to draw vulnerability is the circular limits of the EOL-RIR. The vulnerability is based on the possibility to acquire a material according to fair market or circular source, as recycled materials. Critical materials for the sector intending to secure the production chain could look at circularity and/or market safety. Again, institutional quality is just a 'preventive' measure. It does not state an absolute and unequivocal standard of violations. In this application, we see that most green materials are outside the comfort zone of fair and recyclable materials; a synthetic graph of the analysis is portrayed in figure 4, along with the distinction areas we previously mentioned.

With a wider perspective on all examples, we could outline a trade-off between circularity and institutional quality. The correlation for EEE is -26.5%, for solar panels is -37.2%, for EV -22.9% and finally Wind farms is 24.0%. Its relevance in this chapter is to prove the inverse relation between Index M and EOL-RIR in CRM. The calculation has been made on all CRM according to the report of the EU commission. We collected the relevant information in table 1; the total panel of materials is referred to the category of Electrical and Electronic Equipment (EEE). They design all commodities that are designed to function via electricity. We used EEE as yardstick configuration as they contain almost all CRM. Its waste designation is named waste EEE (WEEE) according to EU packages of 2008 and 2014. A recent report highlighted that these commodities are normally not designed to be fully recycled

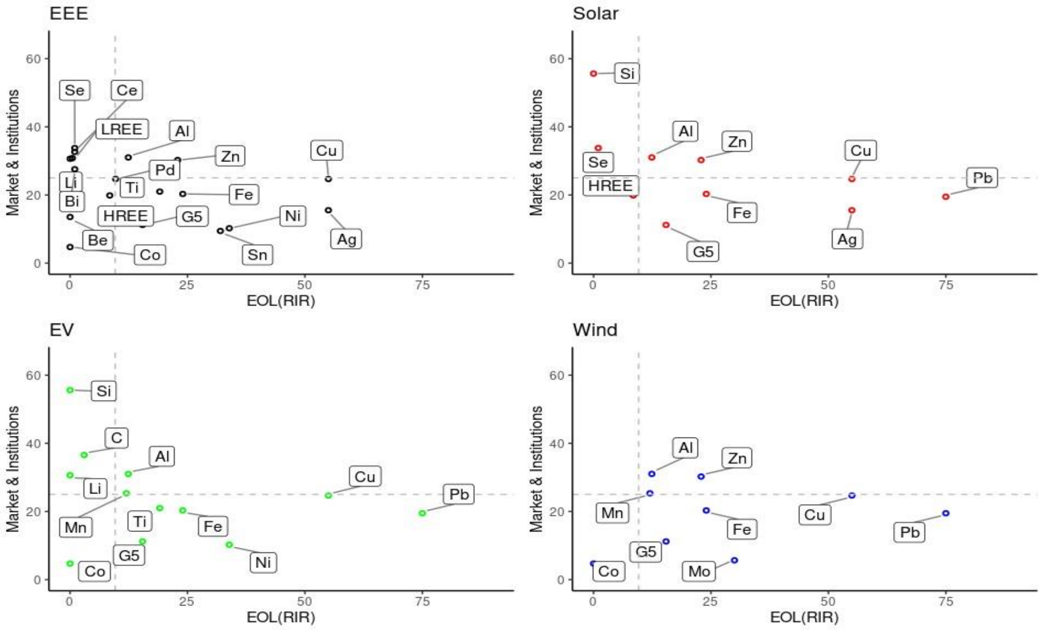

Figure 6: Sector allocation of CRM

(Raudaskoski et al., 2019). They are relevant for the circularity strategy, and usually, the other three products are considered related to them for sustainable electricity generation and components (accumulators). Therefore, we split materials according to the uses in three sectors of the Green Transition. These are Solar panels, electric vehicles (EV), and wind farms. The highlighted trade-off is present in both solar farms and EV. The difference between sector vulnerability is represented in figure 5.

Wind farms are based on materials characterized by a heterogeneous set according to circularity and generally tainted markets. Solar farms register some materials in the comfort zone, such as Copper and Zinc. Outside HREE and G5 materials, it is overall a safe sector. Some materials could be recovered by discarded (Iron, Silver, and Lead) others acquired on fair markets (Silicon, Aluminium, and Selenium). Wind farms rely mostly on tainted markets, whereas most of them quickly recover from European scrap metals (Copper and Lead). Unfortunately, Cobalt and G5 are necessary for components, endangering this sector for both circularity and production chain fairness. Finally, EV CRM is characterized by both trade-offs and deep criticalities. Due to the level of technological complexity, this should not sound surprising. It is nonetheless relevant to point out that both Lithium and Cobalt, the lowest in EOL-RIR, are required. According to our result, lithium is significantly safer than most other recyclable materials but not within the trade-off. These two are, according to our criticality, the most difficult to control for a sustainability transition. The European production chain for transition commodities such as these is vulnerable in the following decades without institutional quality and recycling technology improvements. In this section, we briefly classified materials according to an index "M" and EOL-RIR. The first evaluated jointly market concentration and institutional quality. It penalizes extensively materials that are concentrated in fragile states. EOL-RIR refers to the recycling potential of the referred material. A brief discussion over the results will classify the focus of policies.

Table 2: Summary table for Criticality assessment

HS92	M index	EOL(RIR)	Cartesian D	Chemical Name	Application	Main Trader
2613	5.68	30.00	30.532	Mo	Wind	CHN (31.036%)
250410	36.57	3.00	36.693	C	EV	CHN (10.46%)
251910	29.18	9.50	30.686	Mg		IND (23.039%)
252010	32.57	1.10	32.589	Ca		ESP (5.29%)
260111	20.31	24.00	31.439	Fe	Solar, Wind, EV, EEE	BRA (11.134%)
260200	25.34	12.00	28.040	Mn	Wind, EV	GAB (17.484%)
260300	24.69	55.00	60.289	Cu	Solar, Wind, EV, EEE	BGR (8.882%)
260400	10.24	33.90	35.412	Ni	EV, EEE	CHN (40.858%)
260500	4.73	0.00	4.729	Co	Wind, EV, EEE	AUT (28.584%)
260600	31.03	12.40	33.413	Al	Solar, Wind, EV, EEE	GIN (17.477%)
260700	19.49	75.00	77.490	Pb	Solar, Wind, EV	BLX (7.352%)
260800	30.26	22.90	37.945	Zn	Solar, Wind, EEE	BLX (7.772%)
260900	9.44	32.00	33.364	Sn	EEE	MYS (31.452%)
261400	21.00	19.10	28.383	Ti	EV, EEE	BLX (9.73%)
261590	11.22	15.43	19.079	G5	Solar, Wind, EV, EEE	BRA (23.849%)
261610	15.53	55.00	57.152	Ag	Solar, EEE	BOL (8.522%)
280450	19.09	1.00	19.115	Te		CHN (15.148%)
280490	33.78	1.00	33.798	Se	Solar, EEE	DEU (6.511%)
280530	19.87	8.45	21.589	HREE	Solar, EEE	CHN (11.598%)
282560	29.99	1.70	30.040	Ge		JPN (6.044%)
283691	30.65	0.00	30.648	Li	EV, EEE	CHL (11.023%)
284610	32.64	1.00	32.651	Ce	EEE	JPN (20.777%)
284690	30.81	0.50	30,815	LREE	EEE	JPN (15.431%)
391000	55.63	0.00	55.628	Si	Solar, EV	BLX (5.368%)
711019	26.68	11.50	29.054	Pt		ZAF (23.751%)
711029	24.72	9.70	26.555	Pd	EEE	RUS (34.217%)
810600	27.57	1.00	27.590	Bi	EEE	CHN (19.52%)
811219	13.55	0.00	13.549	Be	EEE	USA (20.995%)

Discussion

Circularity and RS collect strategies intended to reduce the harmful effects of external dependency. Since the EU is abiding by OECD Due Diligence practices, imports must conform to international standards. However, indicators for human rights violations are sparse, and data clearance is one of the main pillars of Due Diligence. Efforts to create a consensus have been made (OECD, 2020). Using national-level indicators for institutional quality allows having a homogenous measure, comparable between suppliers and between sectors. Using such indicator along with market concentration is possible to identify the nodes of monopoly and political instability. Reducing dependencies from fragile nations (or fostering their development) represents a strategy for external risk mitigation. Investing in recycling technologies and enforce circularity policies reduce internal vulnerability: the lack of relevant raw materials' deposits.

Demand for green transition commodities still is dominated by the European market. EU represents the destination of most of those raw materials their risk. The focus on GDP use in criticality analysis is redundant in these terms. The main vulnerability to recall is to EU welfare. The impossibility to apply carbon-neutral policies and allocate enough EEE affects contemporary and future standard of living. Thus, when considering RS, firms increase their chain's welfare value more than the economic value. In such a sense, GDP is not a measure of welfare (Stiglitz et al., 2018a). It is a common feature to use as an economical substitute when using economic value over the total GDP (Ferro & Bonollo, 2019). In this sense, focusing on critical indicators of circularity and institutional quality allows identifying alternative strategies. For instance, sectors that are characterized by negative correlation could focus on circularity or RS efforts according to their cost function. Such approach could be done with three indicators at time, and could be repeated for as many indicators are necessary. However, literature has demonstrated that the relevance of geopolitical and economic relevance indicators could be redundant.

The Cartesian distance approach has an inherent limitation: it is an indifference indicator. Since our interest was to give no particular preference to the indicators at any level, it does not penalize our results. The higher the value, the safest in the supply line. The Cartesian distance indicator grows logistically with its argumenta values. In case one of the two variables is near zero, the other indicator explains its importance. Therefore, a long distance with one of the two arguments as near-zero indicates specialization possibility. If the application (for instance, solar panel) involves Lead, circular policies could mitigate risks on the supply line. Lead is relatively cheaper to recycle, but the sources are often not institutionally stable. As long as sectors can allocate their inputs according to the correlation, they can maximize their circularity and RS results. Applications of Cobalt are, in terms of RS, the most unsafe. The nearest element in terms of low value is Beryllium with 13.549 points of Cartesian distance. In our study, its applications are mainly concentrated in EEE, in particular for circuits. While its circularity is nearly null, its primary source consists of USA mines. This means that RS strategies might yield better results.

Circularity policies are topical for CRM. Secondary materials substitute virgin materials, reducing dependency on fragile countries. As reported in results and figures 4 and 5, most materials low in the M index have decent EOL-RIR (in many cases debatable, but helpful). Similarly, Cerium, one of the LREE, is low in circularity but worthy in the M index. Sectors that rely on such material could focus on circularity improvements to success in SDG. Overall, commodities related to wind farms and solar panels employ CRM characterized by a decent circularity level: most of them are above the median demarcation line. Complex commodities Such as EEE and EV are unfortunately challenging to manage. EEE is a comprehensive group. However, CRM applications are characterized by stable trade-partners such as Japan. Our analysis may affect, for the most significant part, only some of the commodities within EEE. For instance, ICT-related commodities are composed of a complex CRM set (Kasulaitis et al., 2015), compared to heavy household appliances.

Green transition dependency to CRM does not represent a bottleneck for its policies. Some commodities critical for it could benefit from concentrated efforts on only one of these two: RS or circularity. Solar farms, for instance, use HREE, but most of its materials generally have decent circularity levels. Therefore, improving RS factors by blending the product chain with secondary materials is possible. A similar approach could be made for Wind farms. Energy policies involving such instruments are fascinating nexus for mineral securities and RS. Considering their relatively low risk from sources, they help carbon transition, considering conflict minerals legislation. On the other hand, EVs are a strong driver of carbon-free mobility. Unfortunately, their production relies on several CRM affected by possible conflicts and low circularity.

Conclusions

Although used in low concentrations, the growing market of electronics and transition commodities has increased the global demand for critical materials. This has generated concerns about CRM international reserves and supply since they are either scarce or extracted in a limited number of countries. The main strategies proposed for the mitigation of material criticality are recycling and responsible sourcing (Lapko et al., 2019; Young, 2018). Recycling is likely to reduce input from primary raw materials, although it may not meet the growing market demand for certain materials (Mayyas et al., 2019). RS leverages stewardship and certification programs that support sustainable development and practices in mining countries, steering cooperation among countries and industrial sectors, arguably securing the supply of raw materials (Gandenberger et al., 2012). Both strategies present organizational and operational constraints, besides major technological issues (for recycling). Commonly described as immaterial, digital technology is, on the contrary, high energy and material intensive (see the work of EcoInfo in France. See also Maxwell (2014) and Lepawsky (2018)).

There is now vast literature documenting the materials, infrastructure, labor conditions, and energy requirements underpinning the production, maintenance, and disposal of digital technology. There is still no consensus, however, on which indicators are necessary for disclosure. NGOs and national laws in the US and EU have since recently focused on the supply of "conflict minerals" tin, tantalum, tungsten, and gold. The first two, in particular, are used to produce components of circuit boards and electronic devices). Mining and trade are entangled in conflict and severe social conditions in the Democratic Republic of the Congo (DRC). Demanding enterprises to verify purchased goods as "conflict-free" means that they are not extracted in a conflict zone and used to finance the conflicts in DRC provinces.

Our chapter has presented a criticality study on CRM. To classify the EU's vulnerability in terms of total supply, we considered two aspects: responsible sourcing and circularity. In this sense, the general objective should be to access markets safe from human rights violations and secondary materials. We identified as a proxy variable for human right safety an index of institutional quality. For circularity, we referred to the EOL-RIR as it is generally employed in criticality assessment for CRM; it is a proxy for secondary material recovery. The former relates to the market concentration jointly with the institutional quality of exporters. We elaborated a synthetic index for these two aspects: market/Institution fragility versus circularity, hence internal versus external vulnerability. Using a trivial index generation classification, we presented evidence of a trade-off between circularity and market concentration/institutional quality. According to our results, wind and solar farms' energy commodities represent a safe instrument for transition policies when we consider internal and external vulnerability.

Transition commodities such as EV, solar panels, and wind farms present overall decent average circularity and safe external sources when the former is lacking. The sector of EV represents for both methodologies the most critical sector for circularity, market vulnerability, and human right violation. According to these results, it represents liability risk, the sector with the most significant liability risk for responsible sourcing and material circularity. The exponential growth of markets for electric vehicles is likely to put pressure in the short and medium-term. Our preliminary results show that beryllium and Cobalt commodities traded in Europe present criticality from the institutional quality and circularity perspective. The methodology applied is not necessarily bound to application in CRM. Energy commodities such as gas and oil are affected by similar performance. Instead of circularity, climate impact could be possible substitutes. Overall, the chapter presented results on non-energetic elements using two main aspects. This limitation could hinder the completeness of our products. However, indicators of RS could greatly vary between commodities and nations. Circularity is based upon industrial definitions; thus, fewer indicators could be considered alternatives to EOL-RIR. Finally, RS and circularity represent a gap in the literature. While our study is not intended to give a complete toolkit for supply strategy, it identified an exciting advantage point.

Better knowledge of the complex supply networks of CRMs for Europe can provide several insights for European policymakers. Consensus over RS indicators is vital for this purpose and represents a relevant gap in the literature. It ought to be further explored to support the development of cooperation programs and actions (e.g., the Clean Cobalt Initiative). The challenges for a sustainable transition consist in the discovery of more innovative technologies, as well as to rethink commodity design to improve their durability and reparability. Improved interaction with local communities might strengthen supply security even when national indicators might say otherwise. Local realities often constitute particularities.

Chapter 2
Networks of Supply Chain, Addressing Mining Injustices

Abstract

Cobalt and Lithium are critical materials for the development of next-generation technologies. Energy accumulators and electronic devices all contain a certain amount of these minerals. Such elements' versatility and utility come together with the limited number of countries where their extraction and production occur. As the demand for these materials is growing globally, main concerns arise concerning the security of the global supply chain. A criticality that is less considered relates to injustices exercised over populations affected by the extraction and production of those materials. This problem can be traced back at the macro level and in the supply chain from consumption to extraction. In this chapter, we propose a method to assess the risk for major Lithium and Cobalt commodities traded in Europe of being at the origin of social and environmental injustice. To do so, we coupled material flow analysis with information about socio-environmental conflicts. Results are provided graphically and commented along with data synthesis for the years 2015 and 2017. Besides an exponential growth in Lithium trade flows, results confirm that the fragmentation of the global commodity chain makes it difficult to trace back the origin of Lithium and Cobalt commodities entering Europe. As a result, the link between commodity trade and socio-environmental conflicts remains primarily indirect. This makes it more complex to pursue responsible sourcing among downstream producers and consumers. Ending remarks highlighted the limitations of our research, where possible interest for future research may lies.

Abbreviations: Critical Raw Materials (CRM), European Union (EU), Electrical and Electronic Equipment (EEE), Electrical Vehicles (EV)

Violations and Trade: introduction

The thriving market for consumer and portable electronics and low-carbon technologies (hybrid and electric vehicles, wind turbines, and solar panels) is heavily dependent on the availability of critical raw materials (CRMs), with which extraction, production, and trade are associated with various risk factors. In 2013, a study conducted by the European Joint Research Center identified 32 materials as significant for the European energy system's de-carbonization. Some of them are classified as “critical” and included in the EU critical raw material list being either scarce or extracted in a limited number of countries (Blagoeva et al., 2016). Commonly, criticality assessments consider the ‘supply risk’ and ‘economic importance’ of the raw material. Supply risk reflects the severity of the impact on the disruption of supply chains. It is based on the concentration of major suppliers and their political stability (provide, for example, by the World Banks’ Governance Indicator or the Failed State Index); economic importance reflects the sum of the value of end-use sectors that consume the raw material (Song et al., 2019b). Other studies also include analyses of the reserves and amount of raw materials confirmed and can be economically recovered with currently available technology. Cross-referencing this data with the annual global and projected consumption, it is possible to estimate depletion rates for such reserves with a long-time focus.

Notably, the designation of a material's criticality involves uncertain dimensions, such as predicting technological change, knowledge of sources, and potentially commercially sensitive information on reserves (Deutz et al., 2017; Moss et al., 2011). Other environmental and social criticalities are related to the extraction and processing of these metals, which commonly escape policy reports and specialized literature. While manufacturing countries are concerned with securing the supply chain for those materials, mining in supply countries is entangled with severe social and environmental justice questions. On the other hand, EU institutions underpinned circularity as a complementary tool for material extraction. Thus, firms that intend to adapt their production to attain sustainable Development Goals could mix the two approaches altogether. With circularity, we refer specifically to the retrofit of material waste as secondary material.

Within relevant sectors for the green transition stand Electrical and Electronic Equipment (EEE), wind farms, solar panel, and electrical vehicles (EV). Such sectors have a strong dependence on critical raw materials CRM. Since their demand is expected to rise, we believe criticality assessment of Responsible Sourcing and circularity should study their material inputs. In this chapter, we collected information on the supply chain of Lithium and Cobalt. Using industrial ecology studies results, we matched the total volume of raw materials imported to Europe 28 according to several commodities categories. Reports of Human right violation allowed to trace how much of the total flow could be affected by violations. Since Cobalt and Lithium might be product substitutes, our study suggests that substitution might pay off due to Lithium exporters' better institutions.

There are comprehensive studies on the supply chain of CRMs, Lithium, and Cobalt, for the European Union (EU28) (Deloitte, 2015). Criticality assessments have been presented about reliance on imports and macro-economic factors. However, few studies pay attention to the link between the supply chain of CRMs and environmental and social impacts associated with minerals extraction in mining countries. There is no consensus on human rights violation indicators (Barsh, 1993; Helmut Haberl et al., 2004; Richards, 2000). Since the January of 2021, transparency increases from the Due Diligence practices (EU, 2017; OECD, 2020). Nevertheless, information is available and is of great relevance to orient sustainable sourcing of raw materials from the global market.

The chapter is structured as follows. A literature review studies the previous application of material flow analysis and criticality analysis, and responsible sourcing. We then divided into bottom-up and top-down approaches to evaluate human right violation. Section three presents the materials and methods we use for the criticality assessment. Firstly, we quantify the global flows of the CRM entering the European Union using data available from the United Nations COMTRADE database[1]. To evaluate the quality of the source, we used a top-down method for institution evaluation. In other words, we created an index that mixes six different accounts for institutional quality. Combining it with market

[1] https://comtrade.un.org/ (accessed on 18/09/2019)

representation, we developed an index that expresses both market distribution and quality of institutions. We used data of end-of-life recycling input rates as a proxy for circularity. By plotting these, we split into four areas the material classes. From these results, Lithium and Cobalt were further analyzed in terms of destination of use. Section four presents the discussion and conclusion of our study.

Proxy measures are needed to chart Lithium's geographies and Cobalt commodities' global trade and these materials' actual weight within the commodity chain. Moreover, as most Lithium and Cobalt commodities enter the EU28 as finite products, trace back sources for main manufacturing countries of chemicals and components were necessary. Secondly, we collect data about documented Lithium- and Cobalt-related socio-environmental conflicts in mining and processing countries. Information is taken from the Global Atlas of Environmental Justice (EJAtlas), a comprehensive collection of documented ecological conflicts compiled by scholars in collaboration with activists of environmental organizations worldwide (Temper et al., 2015).[2] Ultimately, we couple quantitative information about Lithium and Cobalt's global trade and the qualitative information about related socio-environmental conflicts to assess the risk of the commodity chains being entangled with greater criticality. Section three synthetically presents the results of the analysis in the form of pie charts and network charts. Pie charts show the origin and quantity of aggregated flow per country and commodity category. Network charts display the trajectories of the trade flows between countries. Section four discusses the results, shortcomings, and bias of our method. Finally, section five concludes with a reflection on the potential impacts and development of this method in further research.

Material and Methods

The quantitative analysis: trade-linked material flow analysis

To estimate Lithium and Cobalt flow entering the EU-28, we perform a trade-linked material flow analysis (MFA) (Sun et al., 2017). Trade-linked MFA makes it possible to estimate Lithium and Cobalt's amount within the whole commodity chain, including raw material extraction, chemical production, component manufacturing, finite product assembly, and eventual recycling. Data on global commodity trade is taken from the United Nations COMTRADE database. We set the boundaries of our analysis to import major commodities containing Lithium and Cobalt into the European Union (the EU28 countries taken together) for 2015 and 2017. The choice of dates is driven to evaluate the impact on international flows after the Due Diligence introduction in 2016 (OECD, 2016a). A similar division has been done in the work of Tagliapietra et al. (2020).

Commodity categories and names are selected from the COMTRADE database. The corresponding mineral content embodied in each commodity is determined regarding ore grades and content ratios. We

[2] The EJAtlas online platform was funded by the European FP7 programme under the project 'Environmental Justice Organizations, Liabilities, and Trade' (EJOLT) in 2012. It was developed at the Universitat Autònoma de Barcelona (Spain) in collaboration with activist organizations.

Table 3: Material Equivalence indicators

Commodity category	HS-code	Commodity name	Cobalt Content	Cobalt equivalence	Lithium Content	LCE equivalence	Sources for Lithium	Sources for Cobalt
Mineral/ chemical	283691	Lithium Carbonate	0	NA	1	weight	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	282520	Lithium oxide and hydroxide	0	NA	0,88	weight	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	282739	Lithium chloride	0	NA	0,87	weight	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	260500	Cobalt ore and concentrate	0,076	weight	0	NA	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	282200	Cobalt oxides and hydroxides	0,65	weight	0	NA	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	282734	Cobalt chloride	0,454	weight	0	NA	Sun et al. (2018)	Chen et al., (2019)
Mineral/ chemical	260400	Nickel concentrate & ore	0,009	weight	0	NA	Sun et al. (2018)	Chen et al., (2019)
Primary batteries	850650	Lithium primary cells and batteries	0,006	kg/item	0,001175	kg/item	Sun et al. (2018)	Chen et al., (2019)
Secondary batteries	850730	Electric accumulators, nickel-cadmium	0,006	weight	0	NA	Sun et al. (2018)	Chen et al., (2019)
Secondary batteries	850750	Electric accumulators, nickel metal hydride	0,0009	kg/item	0	NA	Sun et al. (2018)	Chen et al., (2019)
Secondary batteries	850760	Electric accumulators; Lithium	0,006	kg/item	0,28	weight	Sun et al. (2018) and Zubi et al. (2018) assuming normality	Chen et al., (2019)
Electronics	851711	cordless handsets	0,00054	kg/item	0	NA	Sun et al. (2018)	Chen et al., (2019)
Electronics	851010	Shaver with electric motor	0,00018	kg/item	0	NA	Sun et al. (2018)	Chen et al., (2019)
Electronics	852580	Television cameras, digital cameras and video camera recorders	0,0024	kg/item	0,0012	kg/item	Sun et al. (2018)	Chen et al., (2019)
Electronics	852530	Television cameras	0,0024	kg/item	0,0012	kg/item	Sun et al. (2018)	Chen et al., (2019)
Electronics	852540	Still image and other video camera recorders	0,0024	kg/item	0,0012	kg/item	Sun et al. (2018)	Chen et al., (2019)
Vehicles	870380	Electric Vehicles	0	NA	14,9	kg/item	Sun et al. (2018)	Chen et al., (2019)
Battery	870321	Automobiles w reciprocate piston engine displacg not more than 1000 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870322	Automobiles w reciprocate piston engine displacg > 1000 cc to 1500 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870323	Automobiles w reciprocate piston engine displacg > 1500 cc to 3000 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870324	Automobiles with reciprocating piston engine displacing > 3000 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870331	Automobiles with diesel engine displacing not more than 1500 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870332	Automobiles with diesel engine displacing more than 1500 cc to 2500 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	870333	Automobiles with diesel engine displacing more than 2500 cc	1,8	kg/item	0	NA		Chen et al., (2019)
Battery	851390	Electric lamps, designed to function by their own source of energy	0,00018	kg/item	0	NA		Chen et al., (2019)

select the following commodity categories: 1) Lithium and Cobalt minerals and chemicals (e.g., Lithium carbonate, Lithium oxide and hydroxide, Lithium chloride; Cobalt ore and concentrate, Cobalt oxides and hydroxides, Cobalt chloride, Nickel concentrate & ore); 2) electronics, including portable computers, telephones, cordless; 3) primary and secondary batteries; 4) vehicles. Equivalences for the estimation of the mineral content of each commodity are taken from some relevant academic literature. Cobalt equivalences have been used to calculate aggregate trade flows, as in work by Chen et al. and Sun et al. (2019; 2019). A similar methodology has been applied in the case of Lithium trades (Sun et al., 2017).

We use pure Cobalt for accounting Cobalt flows as proposed by Chen et al. (2019) and Harper, Kavlak, & Graedel (2012), whereas we use Lithium carbonate equivalent (LCE) for Lithium. Most equivalences are provided as a single measure for a wide group of commodities. We had to generalize for one case ourselves. We inferred the composition of secondary batteries following the technological characteristics. In contrast, the technology of secondary batteries is not homogeneous; COMTRADE aggregate all categories in one. Following market shares of secondary batteries (Azevedo et al., 2018) on technology classification and Lithium composition of accumulators, we assume normality of technology distribution. The number of leading technologies that secondary batteries carry is five: Lithium-nickel-Cobalt-aluminum (NCA), Lithium-Cobalt oxide (LCO), Lithium-nickel-manganese-Cobalt (NMC), Lithium-iron-phosphate (LFP), Lithium-manganese-oxide (LMO). The assumption is supported by Lithium iron phosphate technology concentration over the market: almost 45%. This calculation is made by taking information from Zubi et al. (2018) and Sun et al. (2017). This simplification is aimed to calculate the equivalence for the whole category of secondary batteries (or accumulators). The list of all equivalence numbers constitutes a data frame used to aggregate trade flows. Commodity trade flows are then obtained from the COMTRADE database using two different datasets: the first one includes the flows of all registered imported commodities into EU28 countries. The second dataset contains the countries of origin of both Lithium and Cobalt minerals and chemicals [3](the first seven rows of Table3); this dataset is fundamental for coupling quantitative and qualitative data as we discuss in literature. These heterogeneous data frames contain non-aggregated quantities in terms of net kilograms and number of items according to each commodity code. Furthermore, they contain one vector for the origin of the imports and one for the arrival. Two more steps are required for the purpose to extract Cobalt and Lithium fluxes.

The literature gives two central units of equivalence (see Table1): mineral percentage by product weight (express in “weight”) and unit (express in kg per item). Using object-oriented programming[4], we assigned the equivalence value of commodity codes from Table1 to each data frame using an index of

[3]We take as reference USGS mineral yearbooks for Lithium and Cobalt of 2015 and 2017

[4]We used R language following Raimund (1992)

the numeric code and the reference unit as the condition. We obtain a data frame that contains commodity origin, category, and aggregated mass of Lithium and Cobalt from this association. This information is used to generate general statistics in the next section.

The qualitative analysis: Lithium- and Cobalt-related socio-environmental conflicts

Its authors describe the Global Atlas of Environmental Justice (EJAtlas) as an “online database and an interactive map that documents global socio-environmental conflicts, defined as mobilizations by local communities against particular economic activities” (Temper et al., 2015). It maps the patterns of injustice and exploitation along some major commodity chains, from extraction to production and final disposal. At the time of our consultation, 2865 conflict cases were reported by the platform, ranging from mineral ore exploration to water access and distribution conflicts, deforestation, uncontrolled dumpsites, mineral processing, etc. The platform allows users to browse conflicts according to conflict type, country, company, and commodity, filter relevant fields in the database and report new cases by filling out a survey. Conflicts are presented through legal cases, campaigning, petitions, demonstrations, boycotts, strikes, and other forms of action. Although available information differs across world regions and cases, the platform provides a database for each case containing detailed information about the location, dimension, number of affected populations, and intensity of the conflict estimated according to the magnitude of the mobilization, which enables the comparison between cases.

We browsed conflicts according to the ‘Commodity’ tag ‘Lithium’ to obtain Lithium related conflicts from the Atlas. Results highlight two conflicts of medium intensity located in China—one in a prefecture of the Tibetan plateau and related to Lithium-mining operations that caused major river pollution and protests by the local population, and one in Shanghai related to the plans for a Lithium battery plant in the city outskirt, canceled in 2013 after protests from local residents. Seven conflicts are located in the “Lithium Triangle” of South America: one in Bolivia of low intensity (at the Salar de Uyuni); two in Chile of medium intensity (at the Salar de Atacama, and the Dunas e Putù) and four in Argentina (all of the low intensity except one of medium intensity), all related to Lithium-mining operations that are contested by local and indigenous communities for threatening the scarce water resources of these arid regions.

As for Cobalt, since no specific tags are given for it in the atlas, we carry out a visual search among the 587 cases filtered according to the "category" of conflicts "Mineral ores and building materials

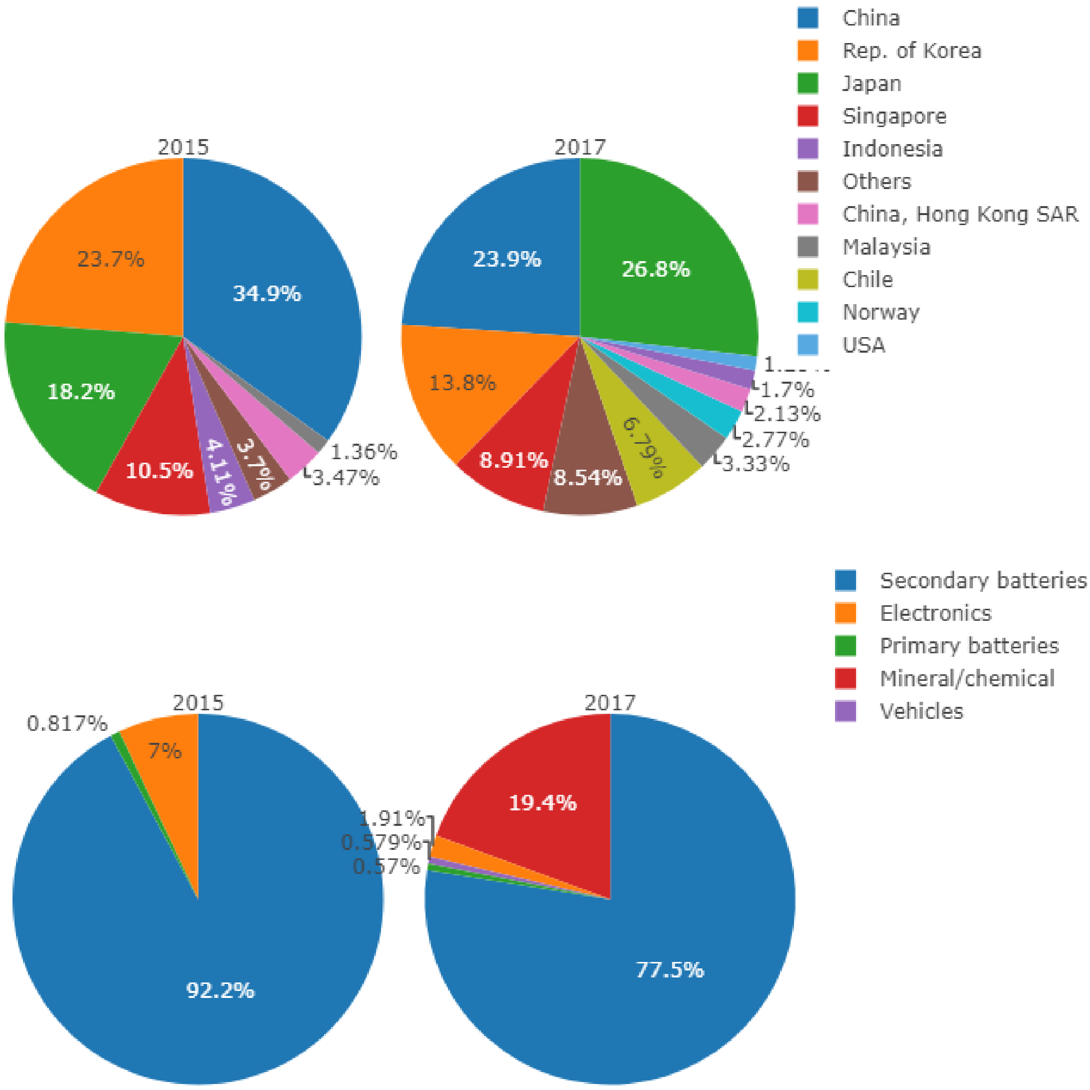

Figure 7: Origin of major Lithium inflows in Europe and distribution by commodity category for the year 2015 and 2017 (source: COMTRADE; elaborated by the authors)

extraction". Our selection results in six conflicts imputable to some sort of Cobalt production: one in Congo of high intensity, two in Zambia of latent and medium intensity, and one in Morocco, the Dominican Republic, and Canada, each of medium intensity. This operation requires a certain amount of time. Still, there is no alternative since Cobalt does not appear in the atlas as a single commodity. It is a by-product of the extraction and processing of other commodities such as nickel and copper. See table 2 for the list of conflicts retrieved from EJAtlas.

Results

The trade-linked material flow analysis

MFA results show that the largest exporters of Lithium commodities into the EU28 for 2015 and 2017 are China, Japan, South Korea, and Singapore, with changing orders over the two years. None of these countries—except China, and albeit to a limited extent is a Lithium producer, which suggests Lithium enters the EU28 mainly in finite products rather than raw material and chemicals. The analysis of the trade confirms this flows by commodity category, dominated by secondary batteries. Total Lithium inflow in Europe amounts respectively to 52583.53 and 155770.90 tons for the years 2015 and 2017. Chile appears among the top ten exporters in 2017, whereas it was previously absent in 2015. This is reflected in the analysis per commodity category that presents a share (20%) of global inflows from raw materials and chemicals for 2017 that is absent in 2015. Data for 2017 also shows a greater number of countries exporting Lithium in 2015, covering together about a quarter of total trade in Lithium commodities (see Fig 7).

Table 4: Location and intensity of Lithium- and Cobalt-related conflicts

Lithium	**N°**	**Country**	**Regions**	**Prefecture/ Province**	**County**	**Date**	**Source**	**Intensity of conflict**
	1	Argentina	Cuyo	Province of San Luis	San Luis	2017	ejatlas.org	1
	2			Catamarca	Salar del Hombre Muerto-Antofagasta de la Sierra	2000	ejatlas.org	1
	3			Salta y Jujuy	Departamento Rinconada (Jujuy) y Departamento La Poma (Salta)	2010	ejatlas.org	2
	4			Jujuy	Salar de Olaroz-Cauchari, Argentina		ejatlas.org	1
	5	Bolivia		Potosì	Daniel campos y Nor Lipez- Salar de Uyuni	2009	ejatlas.org	1
	6	Chile	Maule	Conception	Dunas de Putù	2010	ejatlas.org	2
	7		Antofagasta	Province of El Loa	Salar de Atacama	2009	ejatlas.org	2
	8	China	Qinghai	Karze Prefecture, Sichuan province	Dartsedo County	2005	ejatlas.org	2
	9		Zhejiang	Shangai	Xiaokunshan Town, Songjiang District	2012	ejatlas.org	2
Cobalt	10	Canada	Labrador	Voisy's bay			ejatlas.org	2
	11	Congo					ejatlas.org	3
	12	Dominican Republic		La Vega		2007-2013	ejatlas.org	2
	13	Morocco		Ouarzazate		2011	ejatlas.org	2
	14	Zambia		Copperbelt			ejatlas.org	0
	15					2004	ejatlas.org	2

Legend: 1-Low intensity (some local organizing); 2-Moderate intensity (street protests, visible mobilization); 3-High intensity (widespread, mass mobilization, violence, arrests, etc…)

Among these countries, and since the variance in market shares is skewed towards countries with greater exports, we cluster minor exporters not capable of covering a market share of more than 1% as “Others”.

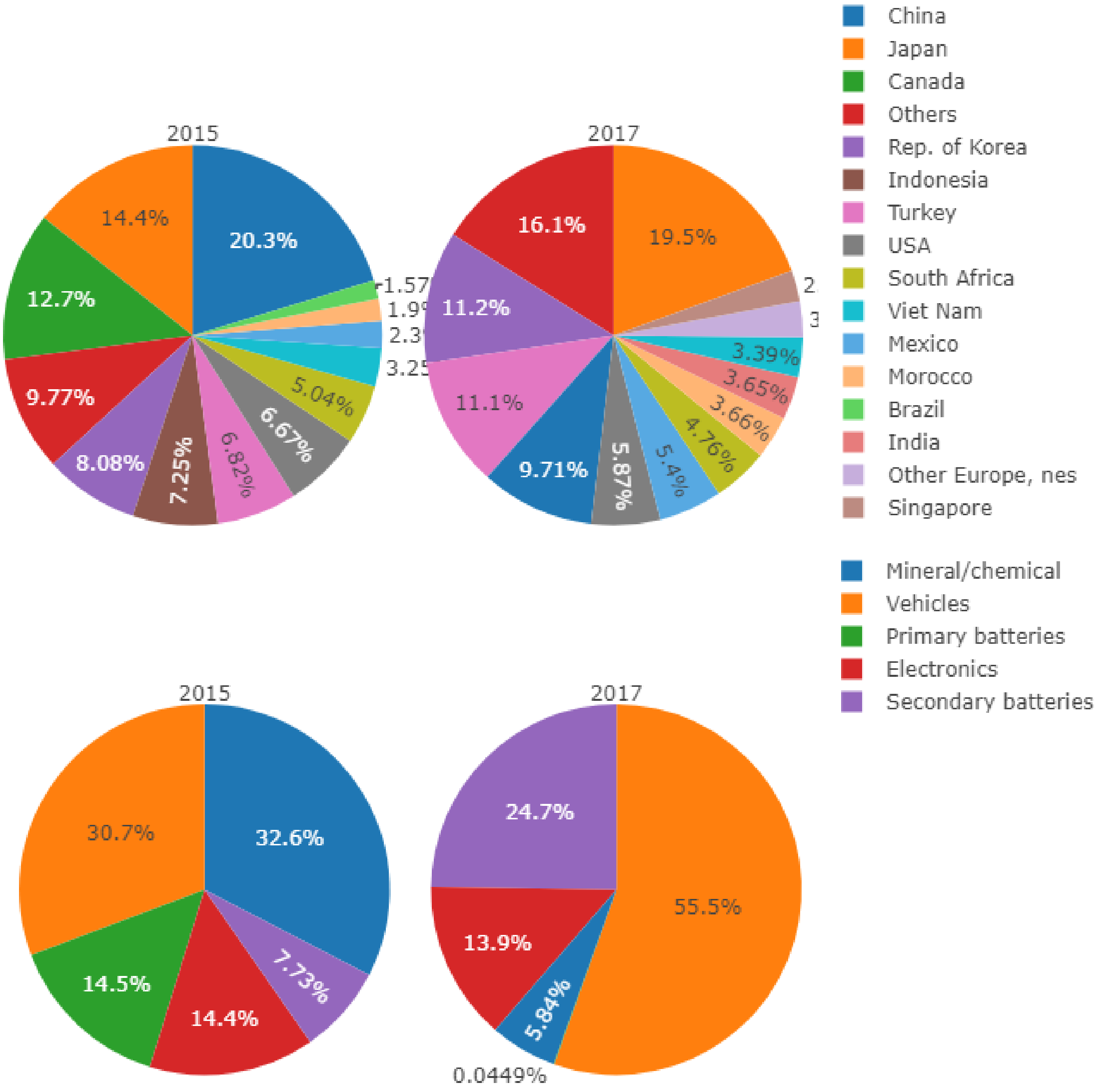

Figure 8: Origin of major Cobalt inflows in Europe and distribution by commodity category for the year 2015 and 2017 (source: COMTRADE; elaborated by the authors)

Cobalt's main sources of imports into the EU for 2015 and 2017 are China, Japan, South Korea, Canada, and Turkey. Again, data shows no direct trade from mining countries, and RDC is arguable since most of Cobalt enters the EU as a component of finite products. Here, more than for Lithium, a greater number of countries contribute to the lesser and equal extent to the global trade flows. Taken together these countries account for about half of all imports into Europe. This share increases between 2015 and 2017, contributing to the fragmentation of the Cobalt flows. The total inflow of Cobalt is respectively 15131.20 tons in 2015 and 11613.68 tons in 2017, registering a 23.25% reduction between the two years. Aggregation by commodity categories shows that most of Cobalt enter the EU as part of vehicles followed by electronics (for 2015) and secondary battery (for 2017), with the presence of a share of raw materials and chemicals for both 2015 and 2017 (to a smaller extent) (see Figure 8).

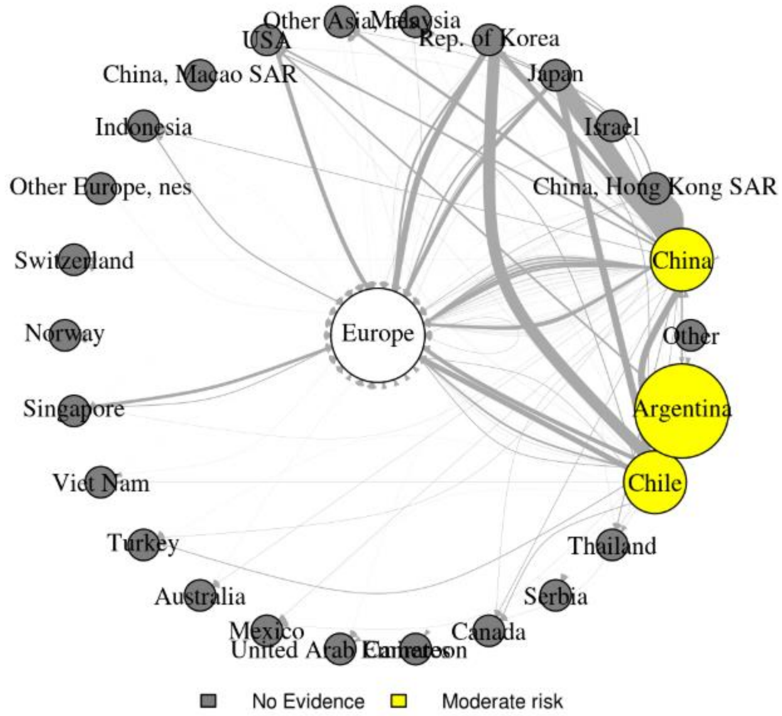

Figure 9: Network chart of major Lithium trade flows to Europe and between tier countries and related conflicts (source: COMTRADE, EJAtlas, elaborated by the authors).

Coupling data about global Lithium and Cobalt flows and documented related conflicts can provide an overview of the risk of these commodity flows be at the origin of social and environmental injustice. We present this in the form of network charts made of nodes and edges: the edges represent the aggregated flows of materials, and their thickness is proportional to the weight (in tons) of flows. The nodes represent the countries of origin and destination of these flows, with Europe (the final destination) placed in the chart's center. This allows highlighting information obtained from EJAtlas about documented socio-environmental conflicts documents for the countries that appear in the network. We attribute to the nodes a value from one to three according to the presence/absence, number, and intensity of conflict (low, moderate, or intense). We use different colors to indicate the existence and intensity of conflicts. The node's size indicates the number of conflicts. Since European countries do not necessarily directly import raw materials but finite products, we added to the edges data frame a second dataset about intermediaries in the commodity chain obtained from the COMTRADE database. This data frame contains exports from main global supplier countries as indicated by the USGS report for the year 2015. The resulting charts show trade-linked material flows of Lithium and Cobalt between Europe and the exporting countries and between the countries themselves (see Figures 7 and 8). It also highlights where the conflicts documented by EJAtlas are located and their intensity.

The result (see Figure 9) shows that most of the Lithium entering Europe is likely to originate from China, Chile, and Argentina, as those countries are not only among the main exporters to Europe (China and Chile) but also export to intermediaries that trade finite products to Europe, such as China, Japan, South Korea, and Hong Kong. Surprisingly, we record no flows from Australia. However, this country is one of Lithium ore's largest global producers: it means that mineral sources coming from such country are not registered by COMTRADE or its flows are directed to other non-European countries. The former reason is proven by the lack of registered exports from Australia in 2015 and 2017. Secondly, when the network was modeled, several micro transactions (below 100000) had to be eliminated. The figures regarding the networks presented the main exporters rather than all the original sources. These countries are also those for which EJAtlas documents the greatest Lithium related conflicts. One possible reason to explain such dynamic is the manufactured-driven demand from European Union that displace raw materials. Therefore, regions and states that mainly export raw materials are generally excluded.

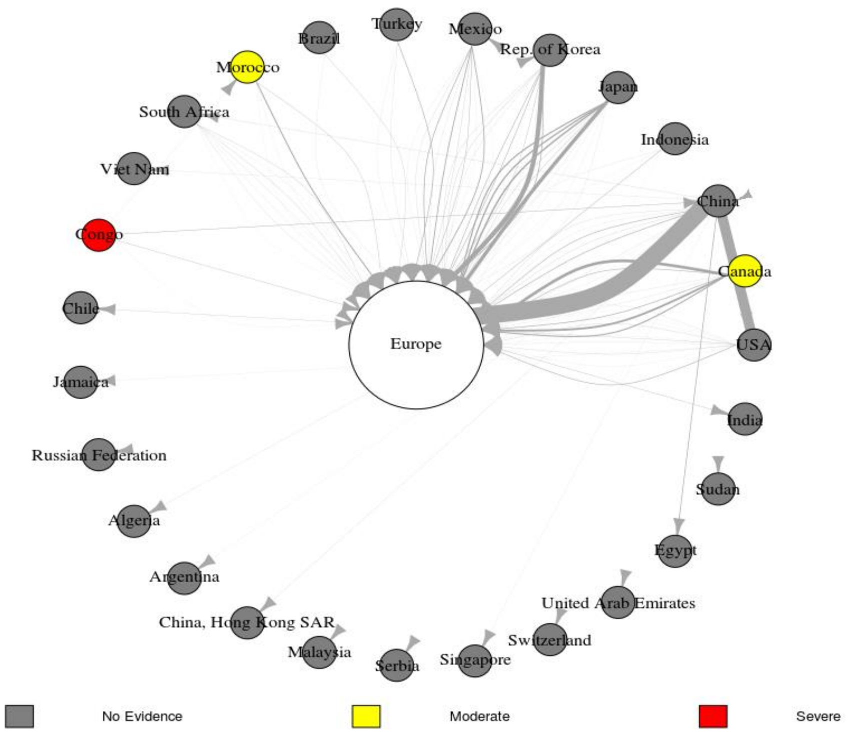

Figure 10: Network chart of major Cobalt trade flows to Europe and between tier countries and related conflicts (source: COMTRADE, EJAtlas, elaborated by the authors).

As for Cobalt (see Figure 10), except for China who's leading the global exports into Europe, the chart shows a more evenly distributed supply network with contributions from a multitude of countries. Countries with documented conflicts in the chart are Morocco, Canada (moderate intensity), and Congo (of severe intensity). Although the main outflow from Congo is directed to "Other" countries, the triangulation between RDC, Morocco, and EU suggests that Morocco could be an entry point to Europe of Cobalt from RDC.

Discussion

Our trade-linked MFA confirms that Lithium consumption in Europe has grown significantly between 2015 and 2017. For Cobalt consumption, on the other hand, the datasets we collected do not indicate significant variations between the same years. Moreover, it confirms that the bulk of Lithium exports to

Europe come from some major Asian economies (China, Japan, and South Korea) and that these economies are linked with Chile and Argentina (raw material exporters). On the other hand, the figure for Cobalt results less sharp: exports to Europe, when we exclude China, are more equally distributed among several countries. Commodity choices in our analysis can explain this. Indeed, our initial dataset privileged portable electronics and other small commodities where the consumer choice may be of greater impact. For instance, our analysis excludes Cobalt flows related to the aerospace and heavy machinery sectors, which are nonetheless essential consumers of Cobalt in Europe, but on which we argue the citizen/consumer has little influence.

The second aspect of signaling is the apparent imbalance of material flow between the years of reference. We registered a great difference between manufactured exports and total exports of raw materials from extracting countries. The first explanation of this may be related to material accounting. For instance, exports of Cobalt and Lithium from mining countries are not always the same imports from the same nations. Such imbalances appear already in the literature (Hatayama et al., 2014). A second explanation is technical, as Cobalt and Lithium contents in commodities may vary according to technology evolution over time. Since the equivalence measures were estimated from data of 2012, commodities may have reduced material requirements. It has possibly lead to decoupling in material extraction (Bithas & Kalimeris, 2018).

Documented conflicts linked with the European market are primarily located in South America and related to the mining sector, e.g., tailing dam bursts, conflict over water scarcity, and local conflicts due to environmental pressure and socio-economic problems. In particular, it appears that Lithium production's water intensity raises concerns among the indigenous people in the arid regions of Argentina and Chile, where the world's largest reserves of Lithium brine are found. Here, water is spread out over large surfaces at a level of a few feet deep and left to evaporate for months, moving from pond to pond to concentrate Lithium content which is then separated from the rest of the brine. On the other hand, the main concerns with Cobalt regard mining in Congo, which is partly artisanal and comprises child labor. Here, the mining activity exposes local communities to high levels of toxic metals and water pollution caused by washing the ore.

In our charts, Lithium-related conflicts are concentrated with similar intensities among South American countries and China, which are the main exporters of raw materials to Europe or intermediary countries. Cobalt instead registers a minor number of conflicts but with a higher variance in intensity. This means that Lithium commodities entering Europe are likely to be at the origin of conflict. However, it is difficult at this stage to identify the links between resource origin and consumption. Ultimately, the results of our analysis show that the global trade of these commodities is dispersed. It presents multiple tiers of contract suppliers, manufacturers, and assemblers may render it impossible for final consumers, downstream producers, and even policymakers to allocate responsibility and implement responsible sourcing of raw materials.

In terms of flow changes, total Cobalt and Lithium equivalent trades experienced a reduction in the amount coming from violation-related markets, particularly from China. However, imports from nations related to violations comprise around 35% to 30% for Lithium, between 20% and 10% for Cobalt. The dataset COMTRADE registers an impressive amount of micro-transactions, primarily due to intermediaries: we considered micro-transactions those traded quantities below the 1 million dollars.

Conclusions

Although used in low concentrations, the growing market of electronics and low-carbon technologies has increased the global demand for critical materials and concerns about their international reserves and supply since they are either scarce or extracted in a limited number of countries. The main strategies proposed for the mitigation of material criticality are recycling and responsible sourcing (Lapko et al., 2019; Young, 2018). Recycling is likely to reduce input from primary raw materials, although it may not meet the growing market demand for certain materials (Mayyas et al., 2019). Responsible sourcing leverages stewardship and certification programs that support sustainable development and practices in mining countries, steering cooperation among countries and industrial sectors, arguably securing the supply of raw materials (Gandenberger et al., 2012). Both strategies present organizational and operational constraints, besides major technological issues (for recycling). We know, for instance, that Cobalt has a significant recycling input rate in Europe (35%) (Tecchio et al., 2017). In contrast, Lithium is not recycled since Lithium's recovery from batteries, although technically feasible, is still not economically viable (Lebedeva, Di Persio, & Boon-Brett, 2016).

Commonly described as immaterial, digital technology is, on the contrary, high energy and material intensive (see the work of EcoInfo in France. See also Maxwell, 2014; Lepawsky, 2018). There is now vast literature documenting the materials, infrastructure, labor conditions, and energy requirements underpinning the production, maintenance, and disposal of digital technology. NGOs and national laws in the US and EU have recently focused on the supply of "conflict minerals". Among these, we find tin, tantalum, tungsten, and gold: the first two, in particular, used to produce components of circuit boards and electronic devices. Mining and trade of such materials are entangled in conflict and severe social conditions in the Democratic Republic of the Congo (DRC). The policy objective requires enterprises to verify the trades as "conflict-free", which means they are not extracted in a conflict zone and used to finance the war in certain DRC provinces.

In this chapter, we proposed a method to expand the regard potentially upon all CRMs for Europe. We have tested this on Lithium and Cobalt, two critical materials for developing next-generation technologies. The exponential growth of markets for electric vehicles is likely to put under pressure in the short and medium-term. Our preliminary results show that both Lithium and Cobalt commodities traded in Europe present criticality from a socio-environmental justice perspective. Most conflicts are related to Lithium in mining countries, although conflicts associated with Cobalt are of significant variance and severity. Better knowledge on the complex supply networks of CRMs for Europe can provide several insights for European policy-makers worth exploring further to support the development of cooperation programs and actions (e.g., the Clean Cobalt Initiative). Production and consumption are based on an extractive finite resource economy, often at the origin of socio-environmental conflicts.

Research on indicators of human rights violation and supply disclosure is a green field of study. In terms of firm-level indicators, it might work and ESG scores, influencing literature on environmental, social performances on financial ones. At the national level, the observations are still incomplete. The observatories are not omniscient, while standardized indicators such as the institutional quality index might underestimate overall changes within a nation or positive regional particularism (KUNČIČ, 2014). Therefore, the research on Due diligence is interesting for both macro (international trade) and micro studies.

Chapter 3
Nonlinearity in Municipal Solid Waste and Economic Activity

Abstract

The chapter presents an alternative approach to analyzing decoupling between municipal solid waste and economic activity production. The methodology consists of generalizing the functional form of the statistical model of the environmental Kuznets curve. To avoid one alternative hypothesis's limitation, we developed a small set of alternatives based on estimates' signs and statistical significance. We tested the model for all available categories of municipal solid waste in Italian provinces. The necessity of developing an alternative approach resulted from inconsistencies in past studies within the same policy context. Conclusions from similar statistical methods and models provided contradictory findings for Europe and other regions. The results of our approach suggest that there is no linear correlation between economic activity and municipal solid waste, nor are they (yet) decoupled from economic activity: GDP per capita affects MSW production differently in each province, which is reflected through differences in spatial correlation.

Abbreviations: Environmental Kuznets Curve (EKC), Functional Form (FF), Gross Domestic Product (GDP), Municipal Solid Waste (MSW), Waste Framework Directive (WFD), Waste Framework Package (WFP), Waste Generation (WG)

Introduction

Municipal Solid Waste (MSW) is an inevitable by-product of human activity (Periathamby, 2011). It amounts to approximately 10% of total waste generation (WG) in European countries (European Commission, 2020b; Mourelatou, 2018). The Waste Framework Directive (WFD) of 2008 made MSW management a priority due to the link with consumption and income levels. The issue is even more relevant in developing countries as stated in the World Bank report "What a waste" (Hoornweg & Perinaz, 2012): it highlighted that damages associated with the long-term production of urban waste are severely undervalued and should not be ignored. Moreover, increasing urbanization and densification of urban areas will significantly impact economic development and, therefore, on waste patterns.

Many events have fueled the interest in effective and efficient municipal waste strategies, such as the waste crisis of Naples, Rome, and Milan (Italy) since 1994 (Di Nola et al., 2018). In recent decades, several aspects related to the topic of municipal waste generation and management have been studied by economists, such as illegal dumping (Chifari et al., 2017, 2018; D'Amato et al., 2018; Sotamenou et al., 2019), driving factors of municipal waste generation (Jaligot & Chenal, 2018a; Mazzanti, 2008; Mazzanti et al., 2008; Mazzanti & Zoboli, 2008), and waste collection pricing (Fusco & Allegrini, 2019; Mazzanti et al., 2012).

Recycling is typically referred to as one of the strategies to move from a linear to a Circular Economy (Alaerts et al., 2019). Yet, the capacity to recycle a significant part of MSW is not the only precondition needed to achieve a strictly Circular Economy. While waste is considered an unavoidable variable in a linear economy, its role is more ambiguous in a Circular Economy where actions range from waste prevention to waste production as a source of material and resources. For example, Nelles et al. (2016) describe waste management's transformation into Germany's resource management. While waste becomes a valuable resource, it is still associated with several negative externalities, and it is not clear whether MSW will be beneficial for welfare (Korhonen et al., 2018).

To transition towards a Circular Economy, it is thus essential to understand economic activity and MSW's interaction. Previous studies focusing on this interaction have addressed the two following factors: heterogeneity and functional forms. In this chapter, we aim to address both at the same time. When searching for tipping points, most authors estimate a model that ignores heterogeneity effects. We believe that results might be affected by both heterogeneity and tipping points, which we test for Italy. Italy provides an interesting case study due to the panel's heterogeneity in such a small territory.

We generate additional insight from a case that has produced some inconsistency using the Environmental Kuznets Curve (EKC) hypothesis by applying the spatial parametric approach. Besides economic activity and municipal waste production, other variables are also included, such as tourism, population density, and occupation, to avoid selection bias. Policy breaks are added to control for EU intervention in waste management. The study's novelty consists of introducing a different way of dealing with functional forms, spatial interaction, and policy evaluation at a low aggregation level. The methodological clarification allows for an unbiased effect analysis of currently enforced waste. Without considering properly functional forms and heterogeneity, wait-and-see strategies would be negatively seen, and decentralization efforts in policy enforcement.

Current waste policies differ between countries and regions. In Italy, waste policies are developed at the regional and municipal levels. According to the ISPRA[5] classification, municipal waste generation (MWG) can be divided into four categories: 1) household waste (incl. bulky waste), 2) non-hazardous matter derived from urban economic activity, 3) street-cleaning derivatives, and 4) waste from cemeteries. These data represent the amounts of waste before any treatment occurs: incineration, landfill, or recycling. Decision 2000/532/Ce[6] divided the four categories into 37 groups according to the material composition. Focusing on the "sorted" fraction, we can find paper, glass, plastics, metal, wood, organic, and textile as separate fractions; the other waste streams are mainly registered within the group "selective". Our analysis will focus primarily on the categories mentioned above.

[1] http://www.catasto-ri uti.isprambiente.it/index.php?pg=ru
[6] https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=celex%3A32000D0532

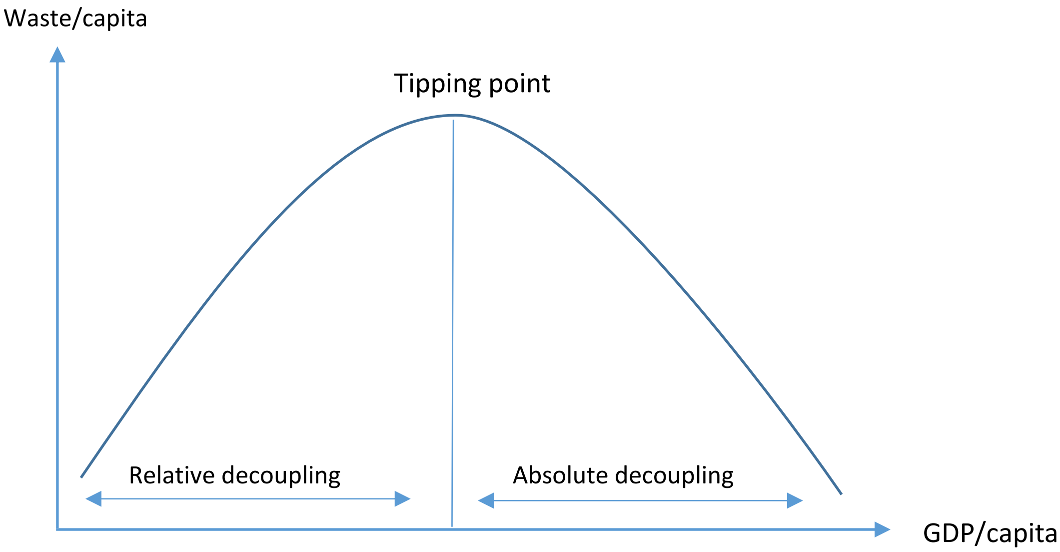

Figure 11: The inverted U functional form and definition of tipping point

Since waste and pollution usually are identified as a by-product of economic activity, national product-waste has been regarded as a topical research matter. Several papers link MSW with GDP. The importance of studying this relationship is highlighted by the idea that a region's economic development might reduce negative externalities while still increasing wellbeing. This phenomenon is called decoupling, and it is frequently studied by estimating environmental Kuznets curves (UNEP, 2011). The Environmental Kuznets Curve (EKC) hypothesized the relationship between environmental degradation indicators and income per capita. In the early stages of development, natural degradation and pollution increase, possibly at lower rates than economic growth. This is called relative decoupling. Above a certain income per capita, named a "tipping point", the trend reverses. At this point, additional economic growth is expected to reduce pollution. This implies that the environmental impact indicator is an inverted U-shaped function of income per capita, as shown in Figure 11. Typically, the indicator's logarithm is modeled as a quadratic function of the logarithm of income (Stern, 2004). However, several critiques of the EKC have been formulated ranging from low-quality data sources, inadequate econometric modeling, and failure to take feedback loops into account, which would allow environmental quality levels to influence economic growth (Lieb, 2004; Perman & Stern, 2003; Seppälä et al., 2001; Uchiyama, 2016).

The chapter is organized as follows. A reference review section follows this one. It conveys a synthesis related to the recent development of EKC and decoupling advances regarding MSW. A table collects the most relevant works, together with the data's geographical location and the analysis results. A methodological section frames the estimation exercise's theoretical premise, providing insights into heterogeneity and multiple functional forms.

Table 5: Overview of studies regarding the link between MSW and income levels

Reference	Framework, Location	Outcome
(Seppälä et al., 2001)	EKC, OECD	No tipping point
(Liu, 2008)	EKC, China	No tipping point
(Mazzanti & Zoboli, 2008)	EKC and convergence, EU28	Tipping point found for landfill
(Mazzanti et al., 2009)	EKC, Italy	Partially rejected[7]
(Mazzanti & Zoboli, 2009)	EKC, EU28	Tipping point (landfill), linear relation (Total)
(Chen, 2010)	EKC-N, China	Two tipping points found
(Yamamoto et al., 2011)	EKC, Japan	Tipping point found
(Hossain & Miyata, 2012)	Data analysis, Japan	Relative decoupling
(Mazzanti et al., 2012)	Convergence, Italy	Convergence found
(Khajuria et al., 2012)	EKC, Japan	Tipping point found
(Trujillo Lora et al., 2013)	EKC, Colombia	Tipping point, landfill
(X. Chen et al., 2014)	Data analysis, China	Absolute decoupling
(Arbulú et al., 2015)	EKC, EU28	Tipping point found
(Ichinose et al., 2015)	EKC, Japan	Tipping point found
(Wu et al., 2015a)	EKC, China	Tipping point found
(Montevecchi, 2016)	Policy analysis, North Italy	Tipping point found for property taxes on waste production
(Gnonlonfin et al., 2017)	EKC, Mediterranean panel	No Tipping point
(Ercolano et al., 2018)	EKC, Lombardy (Italy)	Tipping point (Referring to taxes as ex.)
(Jaligot & Chenal, 2018b)	EKC-N, Switzerland	No tipping point found
(Gui et al., 2019)	EKC, China	Tipping point not found

Literature

Past studies focusing on decoupling between economic growth and municipal waste reveal two aspects: first, decoupling in MSW is not always achieved (i.e., a tipping point does not always exist); second, the results are at best inconclusive. These limitations emerge from an extensive literature review. Twenty articles on EKC (decoupling) and MSW were found by searching Science Direct and Scopus[8]. The outcomes are summarized in table 5. We found that studies for European countries do not produce homogeneous results. These studies mainly use the following approach: testing the validity of the environmental Kuznets Curve with two functional forms and some other proxy variables. These studies do lead to the same conclusion of applicability of EKC for MSW. Each study adapted the exact specification of the econometric model to reflect its specific context: e.g., tourism, policy enforcement, and so on. In most articles, the null hypothesis (H0) represents the EKC hypothesis, and thus, the H0 is

[7] Valid for landfill, linear for total on EU.

[8] The search engines were started the January of 2019 and repeated the December of 2019.

not rejected if all the estimated coefficients of the functional forms are statistically significant. The hypothesis is therefore rejected as soon as one estimated coefficient is found to be insignificant. Table 1 summarizes the methodology, geographical scope, and main result of each study in chronological order. We note that a similar model can have different outcomes for different locations.

Three main methods have been applied to studying the interaction between municipal solid waste and economic activity. The first method is a more qualitative one. It is based on plotting and trend interpretations. The second one uses convergence; this methodology aims to capture trends among changes of rate. When trends are negative, then changes in waste production converge at zero. In other words, proving convergence is equal to finding relative decoupling. This is an alternative approach without strict tipping points. The third method implies the application of functional forms to test the EKC hypothesis. Such a test requires data from the economic and political variables together with the environmental ones. The interaction via regression is supposed to employ linear data, unchanged from non-linear transformation like logarithms. It is possible that with time passing, new entries are admitted to the datasets, changing the result of the test. For instance, Japan has several positive findings for decoupling. China started with negative decoupling (Liu, 2008), and depending on the region, also had the opposite result (Chen, 2010; Wu et al., 2015b). Europe showed unclear patterns, probably due to heterogeneity between and within European nations. The Italian case was one of the most studied. Tipping points and decoupling has been tested on total waste generation and waste shipped to landfills. Results suggest that the economic cycle might affect waste management, but not the production of waste. Still, these two aspects are necessarily interlinked due to the emergence of a Circular Economy. We aim to reduce non-recyclable waste and as recovering and recycling relate to the production of waste.

Testing for tipping points is the operational way to control for the EKC hypothesis. This allows for reducing the observation to a predetermined theoretical assumption (Campos et al., 2005). In other words, the test requires the use of models able to capture non-linear relationships between variables. Previous studies called these models functional forms (FF). These are mathematical formulas that plot shapes like a bell “U”, an “S”, an “N”, etc. The choice of the model is related to the form of tipping points the researcher intends to test. Each FF contains one or more local optima (also called tipping points). The U bell functional form has one tipping point and can be reversed, as shown in figure 11. This is the preferred FF for EKC. The “S” curve is commonly known as a logistic, geometric or sigmoid curve. In economics, it is typically used for predicting trends (Cramer, 2005). The “N” functional form extrapolates two tipping points from data; it resembles one “U” and one inverted “U” altogether (Jaligot & Chenal, 2018b). This form has been used to detect potential decoupling patterns in (panel) data (Gnonlonfin et al., 2017; Gui et al., 2019; Mazzanti et al., 2012; Mazzanti & Zoboli, 2008, 2009; Seppälä et al., 2001). However, some of these articles rejected the H0 based on statistical tests concerning the functional form (Gui et al., 2019; Mazzanti & Zoboli, 2009; Seppälä et al., 2001). State of the art can be summarized in one question: does the EKC-hypothesis apply to the link between MSW and income? As it appears from table 1, two possible answers have been provided. One is yes, and it does, but not for all regions. When the hypothesis seems to hold, income per capita appears to be statically significant as a driver to promote decoupling. However, environmental economists have debated acceptance of EKC (Seppälä et al., 2001; Stern, 2017). The second answer is no when only a linear form is allowed (Jaligot & Chenal, 2018; Liu, 2008; Mazzanti & Zoboli, 2009).

To summarize: the main features of MSW/income literature highlight the limitation of separating the analysis of heterogeneity from the functional forms approach. When assessing heterogeneity, the functional form might seem to be a secondary issue, but we can state the same for functional forms. Spatial regression can deal with both problems. This methodology might cover a gap in the literature. The spatial approach and EKC have not often been studied together. The following section provides the theoretical framework for the analysis, while the heterogeneity component is presented in the data section.

Methodology

When considered in its totality, literature around MSW and income has produced inconclusive results. We believe one of its weak points is functional form and the binary hypothesis approach of EKC literature. The reported articles' approach is to find support for either the null hypothesis (EKC) or an alternative hypothesis based on statistical significance. This first point can be tackled by a multi-functional form approach: considering many functional forms at a time. A second limitation is the rigidity of the alternative hypothesis. Mainstream analysis bases its functional form on the significance of the estimates of a polynomial equation. For example, the bell shape is a second-order polynomial such as $a+bx+cx^2$. The insignificance of the estimate “c” means the bell shape's rejection and supports a linear FF. Similarly, an “N” shape is a trinomial such $a+bx+cx^2+dx^3$: insignificance of d would underpin the “U” form; the insignificance of both “c” and “d” means linear relation between the exogenous variable and the endogenous one. When the third-grade estimates fail, the second-order FF is accepted. When the second-order element is statistically insignificant, a linear relation is assumed for the panel-data under observation. Our approach is designed to deal with the two limitations considered above. The first weakness is dealt with using a family approach, while the second one is dealt with by a decision tree of alternatives. With a family approach, we imply that we use a “family”, a set of functional forms (FF), i.e., a group of functional forms at the same time (see Figure 12). This approach allows us to consider multiple FF. The analysis's heterogeneous component might consider different FF according to spatial unities such as provinces or regions.

The generalization is influenced by the study of the Circular Economy and the separation of waste and externalities (George et al., 2015). Specific approaches regarding the variability of functional forms have been studied before. For instance, Şentürk et al. (2020) suggested that the relationship between economic activity and greenhouse gas emissions presents non-linear FF outside the general prescription of the EKC. Their study estimated threshold values for decoupling. Zapata and Paudel (2009) synthesized the semi-parametric approach towards EKC. Thus, while FF's variability or parametric structure has already been considered before, we present a new application. Besides the particular selection of family, the approach stems from the same theoretical background as the EKC approach. Moreover, the decoupling of environmental damages and economic growth has been explored by the green Solow model of Brock and Taylor (2010).

To account for heterogeneity and different functional forms, we use the following approach. To address heterogeneity, we use a generalization of the exponential components, and we account for provincial

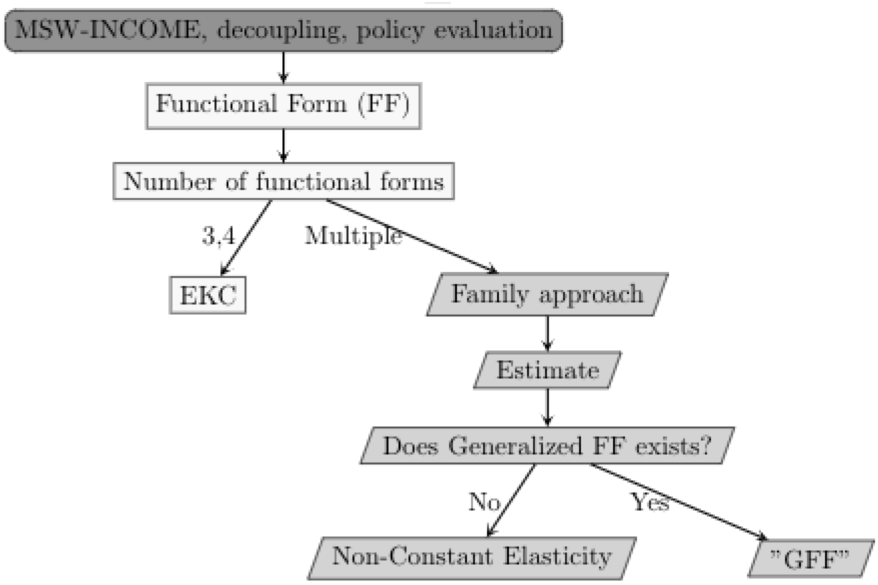

Figure 12: Methodology structure and addition to literature

heterogeneity of FF by using fixed effects. The generalization to a family of FFs is the next step in testing the applicability of the EKC. Figure 12 provides a step-by-step outline of the alternative path. The lighter shapes are the current state of the art covered by the articles mentioned above. The darker ones highlight the contribution of this paper. The generalization represents a family of FF. Since there exists a difference between estimates and FF, a condition of existence is derived mathematically. This step is crucial as it can produce two outcomes. The "family" that is described here covers limited cases and ignores possible interactions between variables. Thus, it is still fair to assume that other FFs exist. When the estimates are outside the domain of possible solutions, the FF is not inside this family. Even if our estimates are significant, it may still be possible to interpret the results differently.

The generalization of FFs can be resumed in the following manner: functional forms vary across countries. Our family of FF starts with a non-specified exponent in the EKC framework. For instance, the classical “U” can be generalized as:

$$y = ax + bx^c \tag{5}$$

Literature has applied the "N" functional form, based on a polynomial of order three (2). In this case, the generalization is:

$$y = ax + bx^c + dx^f \tag{6}$$

These equations can represent the FFs so far analyzed in the existing literature. By generalizing "c" and "f", other functional forms can be represented. We call this a "family" FF, meaning a specific limited number of shapes. The "Y" represents the dependent variable, which is usually MSW per capita in the context of the income-waste relation. The "X" represents the primary independent variable, which is the income per capita in this setting. The third group of exogenous variables, denoted as Z, is used to reflect control variables such as tourism, policy measures, or temporal effects. For simplicity, we now focus on the economic covariate X and add the control variables Z later.

From equation (5), we learn that "a" and "b" must be estimated jointly. In the same way, in equation (6), all variables must be estimated altogether. In large part of the literature, researchers simply assume that c is equal to two, implying a quadratic form. However, there is insufficient evidence to justify this assumption. Thus, we look at the tipping point's first and second derivatives, which most of the studies focus on. The tipping point is defined by equating the first derivate of the y-function concerning x to zero. Based on equation (6), this leads to the following expression of the tipping point (7).

$$\hat{x} = \left(-\frac{a}{bc}\right)^{\frac{1}{c-1}} \tag{7}$$

This tipping point is one-time derivable on "a" while is convex in "b". This is interesting because the sign of "b" determines the convexity of the "U" shape in the classical EKC. We cannot say the same for the parameter "c". For instance, when c is less than 1, both moments are positive in sign. When c is more than one, it means that the tipping point is concave with c. Thus, the sign of "c" is essential as it gives the tipping point dimension, together with "a".

The statistical model's possible determination can be derived from the first generalization's logarithmic transformation (equation (1)). For simplicity, we do not retain Z from the original model.

$$ln(y - ax) = ln(b) + cln(x)$$

$$\frac{ln(y)}{ln(a) + ln(x)} = ln(b) + cln(x)$$

$$ln(y) = ln(a + b) + ln(a^c + b)ln(x) + cln^2(x) \tag{8}$$

The second generalization has a similar process of determination. We start from equation (2) and follow a similar procedure. From (8) we learn that the changes are trivially similar. The main difference is that here we find the third grade x^3 translated to $ln^3(x)$.

$$ln(y - ax) = ln\left(bx^c + dx^f\right)$$

$$\frac{ln(y)}{ln\,(a)\,+ln(x)} = [ln\;(b)\;+cln(x)][ln\,(d)\;+fln(x)]$$

$$\begin{aligned} ln\,(y)\; &= ln(a+b+d) + [ln(a+b+f) + ln(a+b+d) + ln(b+d)]ln(x) \\ &+ [ln(c+d) + ln(a+c+f) + ln(b+f)]ln^2(x) + ln\,(c+f)\,ln^3(x) \end{aligned} \tag{9}$$

Next, the generalization of FF must be translated into a statistical model. This step allows hypothesis testing for the existence of a FF. The framework requires the establishment of vectors and matrixes for variables and regressors. For instance, the matrix $X=\{ln(x\}, ln^2(x\}, ln^3(x\})$ collects the independent variable of economic activity. Vector β comprises the regressor of independent to dependent variables. This has a length equal to the number of grades we are referring to in a mathematical model. For instance, the maximum number of functional forms is taken by the FF resembling the N form. This has a third degrees polynomial; therefore, β has a length of three. Its members are the following: $\beta_1=\{ln(a+b+f) +ln(a+b+d)+ln(b+d)\}$, $\beta_2=\{ln(c+d)+ln(a+c+f)+ln(b+f)\}$, *and* $\beta_3=\{ln(c+f)\}$.

The empirical model aggregates the economic variables in X and the socio-economic controls in Z, while the dependent variable Y is the logarithm of a waste flow per capita. Such a model links GDP per capita with MSW per capita while controlling for other socio-economic drivers. We employ the datasets provided by ISPRA for municipal waste generation and the EUROSTAT[9] database for GDP. Socio-economic drivers have been extracted from ISTAT[10]. This study focuses on the Italian provinces' level, which corresponds to Nuts 3 in the EUROSTAT classification. A province is an institutional level between regions and municipal districts of cities in terms of hierarchy. They do not have relevant policy powers but are useful for data analysis as they aggregate several municipal zones.

$$Y_{it} = \alpha_i + X_{it}\beta + Z_{it}\gamma + \varepsilon_{it} \tag{10}$$

This framework is specific for any case under study. For instance, when no functional form is captured but estimates are significant, we believe another explanation may exist. When estimating EKC, the researcher is interested in finding a tipping point. This happens when at least the order two polynomial of the mainstream model is significant, and the marginal effects are linearly dependent on economic activity:

$$\frac{\partial y}{\partial x} = a + 2bx + 3cx^2 \tag{11}$$

[9] https://ec.europa.eu/eurostat
[10] https://www.istat.it/en/

The tipping point reflects the point where the marginal effect is equal to zero. In other words, when marginal utility generated by economic activity is equal to its marginal disutility. When interpreting them in percentage terms, we refer to elasticity, which in this case, is calculated as follows:

$$\eta_{EKC} = \frac{\partial lny}{\partial lnx} = \frac{\partial y}{\partial x}\frac{x}{y} = \frac{1}{y}(ax + 2bx^2 + 3cx^3) \tag{12}$$

This percentage varies between each level of both income and MSW. In our model, this quantity is strictly dependent on economic activity:

$$\eta_{FF} = \frac{\partial lny}{\partial lnx} = \beta_1 + \beta_2 \, ln\,(x) \; + \beta_3 ln^2(x) \tag{13}$$

In this case, the elasticity is strictly endogenous to economic activity. Elasticity is an intuitive measure of the responsiveness of a variable to the change of another. For instance, MSW is elastic to economic activity when η_{FF} lays outside the interval [-1,1]. Within it, MSW would be rigid to economic activity. When adding spatial heterogeneity, the statistical model must comprise weight matrixes. Here we assume a spatial lag of the dependent matrix:

$$Y_{it} = \lambda W_i Y_{it} + \alpha_i + X_{it}\beta + Z_{it}\gamma + \varepsilon_{it} \tag{14}$$

The lag $\lambda W_i Y_{it}$ indicates the effect that surrounding areas have on the current province. The assumption that spatial dependence affects elasticity highlights variability due to spatial frame. Thus, the elasticity would vary according to socio-economic factors and spatial interactions. In this case, the model might explain different spatial heterogeneity as an interaction between spatial framework and socio-economic dynamics. Thus, elasticity has a different definition:

$$\eta_t^{vul} = \sum_{\forall i}(I_i - \lambda W_i)\frac{\partial Y_{it}}{\partial X_{it}} \tag{15}$$

According to the spatial analysis, the elasticity estimated within one province might be affected by both inner and outer economic activity. The measure used to account for both is called the vulnerability effect (Kelejian & Piras, 2017). We calculated the elasticity as a vulnerability in equation (15). The reporting of such measures accounts for the complexity that can arise from a spatial econometric problem. When estimates are “vulnerable”, policymaking should anticipate the effect on surrounding areas. In this case, the elasticity would be sensitive not only to inner economic activity but also to surrounding socio-economic performances. When the lambda estimate is high (the bounds are [-1,1]), the surrounding area effects are predominant, and there is a high chance of contagion, irrespective of the inner activity. When the estimate is restricted to a value far from the upper bound but not near zero, surrounding effects are added to the inner ones. When it is near zero or even insignificant, surrounding effects are negligible. Estimates found in this way might be similar in the EKC approach but are irreducible to the same hypothesis (Campos et al., 2005).

Data

Before testing the presence of any FF, we need to describe and assess the data structure we use in the analysis. Since we expect spatial dependence, Moran's I test is provided for each time and variable. We also test for autocorrelation and model selection and check for robustness.

Table 6: Summary Table

Variables	N	Mean	SD	Min	Q1	Median	Q3	Max
MSW.CAPITA	1648	520.30	101.19	289.42	454.18	499.18	580.35	864.90
GDP.CAPITA	1648	24304.37	6379.05	11800.00	18600.00	24500.00	28900.00	52400.00
OCCUPATION	1648	0.45	0.33	0.01	0.32	0.40	0.47	0.51
DENSITY	1648	251.91	335.14	31.04	107.65	176.31	275.86	2687.40
PAPER	1648	45.53	34.39	0.00	22.15	44.64	61.52	400.40
ORGANIC	1648	61.75	50.84	0.00	14.78	54.28	100.94	245.50
WOOD	1648	10.47	10.42	0.00	1.69	8.60	16.51	72.37
METAL	1648	5.82	5.20	0.00	1.71	4.81	8.26	37.88
PLASTIC	1648	11.24	9.23	0.00	4.04	8.68	16.51	50.57
RAEE	1648	2.95	2.25	0.00	1.30	2.52	4.43	25.00
SELECTIVE	1648	0.58	1.03	0.00	0.06	0.41	0.83	22.48
TEXTILE	1648	1.45	1.76	0.00	0.43	1.32	1.98	30.21
GLASS	1648	24.09	15.47	0.00	10.44	23.40	36.23	113.20
TOURISM	1648	1381447	2458764	41505	290029	586640	1247583	17383151

A general summary of the variables is reported in table 6. For our analysis, we used a panel dataset with 103 Italian provinces. The dataset covers fifteen years (2001-2016). Note that several institutional reforms had an impact on the exact division of the Italian provinces during this time frame. Due to the reforms of 2007 and 2010, the number of provinces increased from 103 to 107 and 110, respectively. For this chapter, we keep the initial territorial division of 2000. The dataset is generated by combining three open-access datasets: Eurostat, ISPRA, and ISTAT databases. From the beginning, we collected the socio-economic variables such as density, occupation, GDP per capita actualized to 2010. The data comprise the total flow of MSW and all collected sub-flows[11] from the ISPRA dataset. The last database provided shapefiles for spatial analysis and tourist data.

For MSW generation-related variables, we used the ISPRA[12] database, while control variables and spatial data were downloaded from ISTAT[13]. All waste variables are measured in kilograms (kg) per capita. MSW.CAPITA represents the sum of all separated and unseparated classes of waste. PAPER is the collection of paper-made objects, including paper packaging. ORGANIC accounts for discarded food collected in separate bins. WOOD refers to the rest of the garden waste. METAL refers to all metal-made waste, such as cans or plugs. PLASTIC is the collection of all recyclable plastics: for instance, it

[11] A complete definition of nomenclatures used by ISPRA to define flows is provided in appendix.
[12] www.isprambiente.gov.it/it
[13] https://www.istat.it/en/

contains plastic packaging. RAEE represents waste collection from household electrical equipment, commonly known as Waste from Electrical and Electronic Equipment (WEEE). SELECTIVE is the aggregate of different collections requiring a unique class, such as exhausted batteries and medicines. Finally, GDP per capita was taken from Eurostat[14]. Missing data from ISPRA are converted into zeroes. When a province did not have a collection system for a waste class, 0 was reported as a collected quantity. We interpolated the quantity to 0.0001 to extend the time dimension of MSW.CAPITA to all other variables to avoid taking the logarithm of a null quantity[15] (Gnonlonfin et al., 2017). The definition of each waste flow conforms to the EU Commission decision of 3 May 2000. We represented the flow data within the appendix sections.

The exogenous variables can be divided into two main groups: GDP and its polynomial structure ($X_{1:3}$) and a set of socio-economic variables ($Z_{1:3}$). The second group is composed of the potential drivers of MSW typically accounted for in the literature (Ercolano et al., 2018; Mazzanti & Zoboli, 2009). Z_1 represents population density, defined as the average number of residents per year (T) divided by the province's surface area in km^2 (S). Z_2 equals tourism density as the number of days of tourists used hotels, Airbnb, hostels, etc. ISTAT calculates it by the accommodation tax system. We weighted to the area of its province to create touristic density. Finally, Z_3 is the occupation rate defined as the number of employed population residents within the region divided by the total number of residents.

The average income per capita is 24,304 euros within the dataset, while the total MSW per capita is 520 kg. The maximum values for income and MSW per capita were 52,400 euros and almost 865 kg, respectively. The largest category recovered is organic waste, while the maximum registered is paper. The average population density is almost 252 habitants per km^2. The average number of annual tourism visits is 1,381,448 for all provinces, with a maximum of 17,383,151 visitors in 2005 within the province of Rome.

[14] https://ec.europa.eu/eurostat/home?

[15] We run the regression while dropping increasing numbers of lines from the dataset: apparently, most of zeros were at start years, probably for implementation of policy. We dropped from 2001 to 2003 and from 2014 to 2016, reducing the convergence rate from T/N=0.145 to 0.087. The results show minor loss of significance, but signs remain the same and values are close to the reported.

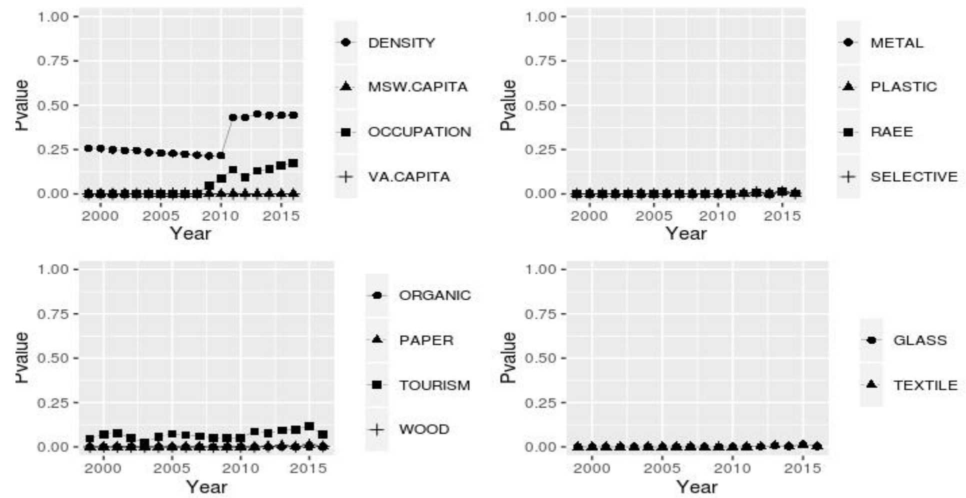

Figure 13: Moran p-value according to year

To integrate the spatial dimension in our regressions, we first generate a normalized spatial weight matrix (W) containing the relevant spatial information. The matrix is first set up as a binary matrix where each cell has a value of 1 or 0, with rows "i" and columns "j" as the number of provinces. The cell w_{ij} contains the value 1 when provinces "i" and "j" share a common border and 0 in the opposite case. Next, the matrix is row-normalized by dividing each w_{ij} is by the number of cells equivalent to 1 in each row. Using this approach, neighboring provinces will receive $w_{i;j} = 1/k$ where k is the neighboring provinces. Islands are isolated, and thus their provinces can interact only with each other. Only one weight matrix is used.

We treated all variables with the Moran test to spot spatial dependence. The test includes the calculation of the Moran I and its p-value. The former can vary from -1 to 1. When equal to zero, it represents a variable distributed randomly. We used the p-value obtained in the Moran's I test for values over 0.1. We could not reject the null hypothesis of spatial interaction. We plotted the results of the test according to each year in Figure 13. Every group variable relates differently to the spatial lag. Thus, each model requires a different pattern of autocorrelation. For instance, we cannot assume randomness in a waste generation; in other words, areas tend to have similar waste patterns. Most of the waste patterns appear to follow this pattern along with tourism density. Population density appeared more random after the reform of 2011. During the economic crisis, the last point was a "surge" in randomness affected density and occupation, probably due to increased population mobility. Thus, we need to add a second lag to the model for socio-economic drivers.

After selecting the spatial matrix and Moran test, we had to determine the models to estimate. Critical aspects under analysis were temporal, local cross-sectional, errors and lags dependence, and fixed effect selection. We reported the results of our tests in table 5 in the appendix. The general equation (14) model was treated for serial correlation in the idiosyncratic component of errors ε. Thus, our model might efficiently use data using individual fixed effects and two-ways and spatial lags. Results show that the tests for local cross-sectional dependence are positive. We tested for spatial dependence in errors; since the Moran test does not have a high p-value, we decided to use the spatial lag model for all categories. The dummies for time and individuals have been tested. We chose to adopt the individual effect to avoid selection bias for redundancy. Since we found spatial interaction for socio-economic components, we included spatial lags of our socio-economic variables in the model. From this set of pre-selection tests, the spatial autoregressive model was identified. The model to be estimated is then the following:

$$Y_{it} = \alpha_i + \lambda W Y_{it} + X_{it}\beta + Z_{it}\gamma + u_{it} \quad (16)$$

Vectors α,β,γ and the value of λ need to be estimated. We assumed that the noise u_{it} is independent and identically distributed in time and space. It is necessary to point out some complex aspects that arose during data analysis. According to the data set provided, most categories were registered as zero kg in the first years of recovery. This notation can produce complications in data analysis: logarithm transformation required interpolation of data. Another option is to remove lines where such matter occurs. We preferred to choose the first to gain as much convergence as possible to estimate maximum likelihood (ML) and generalized moments (GM). From the model selection test, ML and GM displayed similar efficiency. Hence, we choose to use the first method for all except glass. The outcomes of Hausman's test support this choice. Glass is the only material not to support the ML (Table 5). The value of interaction between surrounding provinces is determined by the value of the estimate of λ (Anselin, 2003; Arbia, 2006).

The interpretation of parameter β varies according to the sign of its estimate. When the estimates are all positive, an FF from table 3 can explain income-waste dynamics. When the estimates violate these conditions but are still statistically significant, no known FF can be identified; hence, economic activity is elastic to MSW. More specifically, the elasticity of economic activity to MSW changes according to the level of the former. As expressed in equation 9, the estimates of β_1 represent elasticity at very low GDP per capita values. The other two determine the speed of change according to income and the direction according to the sign. For instance, a negative value of β_2 represents a negative impact of economic activity on elasticity. The third value β_3 in this case, is a second derivative, so it can be interpreted as a "speed of speed" or, in other words, acceleration of change.

This model is helpful for understanding heterogeneity. Each estimate determines one aspect of variable elasticity. Firstly, the interaction between economic activity and waste production is not constant but changes across the spectrum, as is shown by the first two β. Secondly, we can infer how it varies across the GDP per capita spectrum. The second and third β suggest that this variation might be steep or rather flat. In the first case, heterogeneity is large. Thus, elasticity might vary greatly according to GDP per capita. When their value is nearly zero or statistically insignificant, the heterogeneity of elasticity is minimal across GDP per capita levels.

To summarize, the significance of these three βs identifies levels of variability of elasticity. To control for policy intervention, we recall three major breaks. One was the WFD introduction in 2008. This was received as law in Italy the following year. It determines recycling targets and preparing for reuse (more precisely, the target applies to specific types of household and similar waste) (European Environment Agency, 2016; Zoboli et al., 2014). Since our work is related to several flows, we added breaks for the policy packages related to Plastics and Textile flows in 2015 and, finally, the WEEE directive of 2017 (Wilts et al., 2018). These policies aimed at increasing separation level and reducing the MSW per capita produced. The breaks are organized as dummy variables equal to 1 the year after the deliberation. We use a one-year lag as national law adaptation has to take place before experiencing some sort of effects. The value of the dummy is zero before the national law is passed.

Results

Nine ML and one GM model have been estimated. The coefficient associated with economic activity is high and statistically significant in eight of them. Socio-economic variables such as occupation, population density, and tourism visits (q) were consistent with expectations. According to $R^{2,}$ the best fitting models are glass, total MSW, and paper; the least was RAEE (WEEE). The model estimating MSW generation had the minor Akaike information criterion overall. To test the consistency of data manipulation results in section 3, we test the sensitivity by dropping data for some years. We removed 1999 until 2001, where data reported the zeroes. Results show some overall loss in significance as expected but no change in signs. We reported the results in table 3. We find that results vary greatly across the various sub-flows. This variability suggests that some are more dependent on economic activity than other flows. The high β values indicate that sensitivity of scale is lost at very low levels of income when β_2 is negative. This happens, for instance, for the total sum of flows and unsorted waste. The β_1 value is high in all estimations and indicates that the impact of economic activity is very elastic at a low level of income. When the β_1 sign is positive, but β_2 is negative, the elasticity reduces as economic activity rises. Furthermore, this change in elasticity is more sudden as β_3 rises.

We can classify recovered materials according to this estimate into three main categories. The first relates no significant impact of economic activity on waste generation. Results suggest that Paper, Wood, Metal, Plastics, Selective, Glass, and the sum of all sorted flows are not affected by the local economy. The second comprises those flows with a positively elastic impact at low economic activity but becomes rigid steadily or suddenly (according to β_3) inelastic with economic growth: plastics appear to fit into this category. The third category considers those flows with a negatively elastic impact at low economic activity, but which become rigid steadily or suddenly (according to β_3) inelastic with economic growth: Other flows, organic, WEEE, and Textile waste, represent this category.

Variability is very high in textiles and wood. This means that elasticity varies greatly between low-income provinces and high. In this case, low-income regions might have a significant reduction in waste as income rises. Since the change in the degree of variation has a similar tendency, we expect the change to come to a rapid halt. Therefore, variability ceases at a very low level of income. After that point, the percentage variation of economic activity affects textile and wood waste to a similar degree. Plastics and total MSW, on the other hand, act very differently. Elasticity varies slowly in terms of GDP levels. Therefore, heterogeneity across provinces and economic activity is greater and does not behave in the same way as in the previous estimates. While per capita disposal of wood might be similar between average and high-income regions, this is not correct in plastics. Total MSW represents the sum of the other flows. It has the variability of plastics and the signs of wood or textile. This means that the composition, but not the absolute level, of waste, varies greatly according to income. As presented in the data, richer provinces produce relatively more waste than poorer ones.

Policy breaks are statistically significant for most of the flows. The introduction of the Waste Framework Packages (WFPs) induced a reduction in total waste. This is probably related to the partial diversion of unsorted flows into sorted ones. In other words, sorted waste has replaced unsorted. Overall, this phenomenon occurred for the introduction of all three policies considered. The increased sorting generated more specific flows, in particular WEEE and plastics. Uncategorized sorted waste flows, under the heading 'others', were initially diverted due to the WFP and increased due to new additions. The WEEEP has not only had a positive effect in terms of its original objective. All other sub-flows have registered positive increases, reducing the level of unsorted flows. A secondary effect of waste policies was the reduction in total flows.

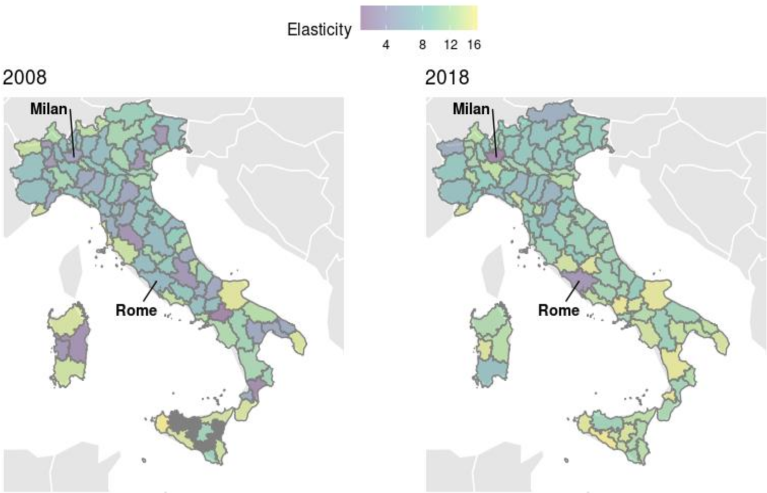

Figure 14: Vulnerability effect of each province 2008-2015

The results do not underpin the hypothesis of weak or strong decoupling. If we take only total economic activity, MSW will probably not respond to economic activity changes after a certain point of growth. As equation (13) points out, we could prove that the rigidity is strictly dependent on economic activity; there is no feedback effect from the scale of MSW as in (14) unless we consider vulnerability.

Other socio-economic variables such as occupation appear to affect the generation of MSW per capita differently, *ceteris paribus*. For instance, plastic waste generation is positively affected by tourism rates, indicating a sector's vulnerability to waste intensity. The same could not be said for glass and paper generation, which are negatively impacted by the surrounding provinces' tourism activity. Population density affects waste generation positively in almost all cases. Italy seems to have similar vulnerabilities for each province. Given spatial interaction, Rome's peak transferred to the south in the province of Latina due to spatial proximity. Despite being both rich cities, Milano (Milan) and Torino (Turin) experience a different scenario. Surrounded by other rich provinces, Milan is the second-highest in Italy for vulnerability. Given the general growth of these areas, vulnerability tends to be higher on average. Southern provinces do not suffer from the same vulnerability, but Bari, for instance, registers a high value. A second aspect arises from this figure. We have explained before that the composition of waste changes greatly according to GDP per capita level. Even by considering spatial interaction, heterogeneity is not fully accounted for as it also varies across time. This outcome is rather complex to interpret, as it assumes that elasticity varies according to the interaction of exogenous and endogenous factors.

Table 7: Regression results

	Dependent variable:												
	Other	Paper	Organic	Wood	Metal	Plastics	WEEE	Selective	Textile	Glass	Sorted	Unsorted	Total
lambda	0.080***	0.199***	0.087***	0.100***	0.045	0.132***	0.141***	0.137***	-0.028	0.119***	0.090***	0.224***	0.586***
	(0.030)	(0.027)	(0.029)	(0.029)	(0.030)	(0.028)	(0.029)	(0.029)	(0.030)	(0.028)	(0.029)	(0.027)	(0.063)
Ln(GDP/N)	-1,679.056***	-10.829	-554.611*	-359.032	191.450	-254.385	-907.747***	-468.551	-999.132***	167.043	-234.054	391.927***	60.497**
	(551.002)	(121.544)	(321.472)	(315.536)	(297.266)	(176.009)	(223.023)	(313.951)	(348.584)	(145.697)	(239.349)	(62.473)	(28.754)
Ln^2(GDP/N)	163.191***	3.640	58.325*	37.488	-16.983	26.736	89.303***	47.194	99.381***	-13.514	26.767	-38.479***	-6.075**
	(54.683)	(12.062)	(31.904)	(31.315)	(29.502)	(17.468)	(22.134)	(31.158)	(34.595)	(14.459)	(23.754)	(6.200)	(2.859)
Ln^3(GDP/N)	-5.281***	-0.200	-2.029*	-1.292	0.498	-0.926	-2.921***	-1.579	-3.288***	0.350	-0.993	1.257***	0.203**
	(1.808)	(0.399)	(1.055)	(1.035)	(0.975)	(0.578)	(0.732)	(1.030)	(1.144)	(0.478)	(0.785)	(0.205)	(0.095)
Unemployment	0.015	0.026***	0.087***	0.034***	-0.026***	0.058***	0.0003	0.028***	0.064***	0.022***	0.043***	-0.011***	-0.004***
	(0.016)	(0.004)	(0.009)	(0.009)	(0.009)	(0.005)	(0.006)	(0.009)	(0.010)	(0.004)	(0.007)	(0.002)	(0.001)
Density	3.172**	-0.399	-4.480***	0.434	-0.408	0.161	2.298***	-2.243***	-2.996***	-0.605	0.169	0.473***	0.777***
	(1.516)	(0.336)	(0.885)	(0.869)	(0.818)	(0.486)	(0.614)	(0.864)	(0.959)	(0.402)	(0.660)	(0.172)	(0.079)
Tourism	-0.405*	-0.117**	-0.256**	-0.120	0.250**	-0.187***	0.140	-0.372***	0.070	0.012	-0.119	0.252***	0.104***
	(0.217)	(0.048)	(0.127)	(0.124)	(0.117)	(0.069)	(0.088)	(0.124)	(0.138)	(0.057)	(0.094)	(0.025)	(0.011)
WFD	-0.431***	0.189***	0.769***	0.334***	0.028	0.453***	0.661***	0.338***	0.266***	0.302***	0.310***	-0.193***	-0.023***
	(0.103)	(0.024)	(0.065)	(0.060)	(0.055)	(0.037)	(0.048)	(0.060)	(0.065)	(0.029)	(0.046)	(0.014)	(0.006)
F&P packages	0.361***	-0.014	0.308***	0.013	0.059	0.215***	-0.046	0.024	0.373***	0.082**	0.144***	-0.158***	-0.023***
	(0.122)	(0.027)	(0.071)	(0.069)	(0.065)	(0.040)	(0.049)	(0.069)	(0.077)	(0.032)	(0.053)	(0.015)	(0.007)
WEEEP	1.131***	0.091***	0.181**	0.224***	0.194**	0.194***	0.126**	0.168**	0.097	0.171***	0.174***	-0.125***	0.008
	(0.146)	(0.032)	(0.083)	(0.082)	(0.077)	(0.046)	(0.058)	(0.081)	(0.090)	(0.038)	(0.062)	(0.017)	(0.007)
AIC	6803.47	1216.90	4806.75	4738.42	4513.25	2577.50	3456.05	4724.53	5103.16	1875.38	3712.86	-1253.55	-2353.55

Note: *p<0.1; **p<0.05

Discussion

MSW management and its economic and environmental impacts have been extensively covered by academic journals and the mass media. Here we study the relationship between MSW and GDP per capita. We highlighted the main limitations in previous studies regarding the methodology for estimating the relationship between MSW and economic activities. One was the FF, and the other was the heterogeneity of impacts. The generalization of FF and the findings of income-based heterogeneity in elasticity constitutes a novelty in the current debate on tipping points. We concluded from the results that instead of changing signs at a certain threshold or reaching a maximum point, MSW generation becomes more rigid as economic activity grows. The second novelty is the approach that underpins such a conclusion. The standard FF approach is modified to contain a set of alternative hypotheses instead of one. We were not able to find an FF that fits all. Still, we manage to interpret the results differently. From our preliminary results, it appears that MSW elasticity concerning economic activity varies. Furthermore, it appears to tend to zero. We interpreted this rigidity to be directly induced by economic growth while controlling for other socio-economic factors. The results show spatial vulnerability: heterogeneity and spatial interactions affect the variation in elasticity across Italian provinces.

These estimates do not consider the policy performance developed by each zone. For instance, despite Milan being one of the most vulnerable provinces, its recovering waste performances are acceptable. It is not possible to say the same about Rome, where vulnerability is present too. In general, and irrespective of the level of expenditure per capita, provinces with high vulnerability may have lower circular performances. The results of vulnerability analysis provide a more systematic effect when perceived in terms of one area. Italy represents the typical example of spatially heterogeneous economic performance. Policies such as decentralization should be considered together when both economic heterogeneity. If taxation reflects income-to-waste elasticity linearly, unfair distribution effects might emerge. Spillover effects induce spatial vulnerability, indicating a spatial distribution of impact. In terms of the MSW-GDP dynamic, the inelastic impact of total economic activity on waste does not mean decoupling *per se*. Structural changes within an economic system can still affect MSW production. For instance, tourism exercises a significant and positive effect on production. Thus, tourism attraction policies could indirectly foster increases in MSW rates, *ceteris paribus*. In terms of policy effects, sorting policies have diverted unsorted and non-specific flows into more specific ones. Sorted materials are generally affected by all policies in place, and signs change only for non-specific flows.

The difference from previous studies is the interaction between spatial framework and EKC hypothesis discussion. This chapter proposes a novel approach by dealing with both matters. We highlighted the possibility that more than one FF arises. Enlarging the scope of approach, we tried to assess why absolute decoupling does not appear in MSW. Given the differentiation of flows and spatial approach, we might have a possible explanation. Each economic level might have different cohorts of waste flows. While some waste flows have almost similar dynamics, others vary greatly. Here lies the importance of non-constant elasticity. A linear framework might have captured different tipping points, but not necessarily the GDP per capita differences.

The economic cycle is affected by location and endogenous variables. This is a reason for using spatial models for EKC. We then used this interaction to highlight the complex relationship between elasticity and income. Some regions have higher spatial interactions. Keeping all constant, provinces influenced by a complex network must consider secondary effects when planning for disposal. This is a crucial aspect of policymaking. Since each province has different GDP per capita levels, waste compositions vary. Since they vary, incineration, landfill, or recycling are strictly dependent on which waste composition emerges in a province. This heterogeneity of composition might be one of the drivers of circular policy. A high level of separation allows for better targeting for recycling.

It is impossible to recover materials or reuse some commodities without sorting them. Decentralization of policy might rule out the heterogeneity of flows if waste separation fuels circular policies. Otherwise, materials are lost in the process. Furthermore, the interaction between areas is relevant for assessing possible changes in waste flows. In some cases, outside MSW policy, a semi-parametric approach to dealing with EKC and its heterogeneity problem has been considered (e.g., Wang, 2013; Zapata & Paudel, 2009). Compared to the spatial autoregressive model, this approach assumes that the distance between a true model and the observation cannot be fully captured. Therefore, estimates follow a non-normal distribution and could vary over time. The approach applied here does assume rigidity of spatial interaction over time. We preferred to use a spatial parametric approach to adapt the decoupling theory to a wider number of FF while taking into account the Italian geographical system. Since provinces are embedded within a rigid scheme of interdependences with surrounding zones called regions, it is reasonable to assume that spatial interaction is fixed over time or varies within predictable intervals.

Another aspect we need to report is the time-varying spatial dependence registered in the Moran test. Such a matter would require an extension (Lee & Li, 2017), but should be covered by a separate study, given its complexity. Furthermore, since clustering on provinces clears out much available information at the regional level, we used available variables but still consistent with the literature. Given the heterogeneity of materials and utility that each good provides, extending the model by using other variables can add interesting knowledge to the field.

Conclusion

This work analyzed the relation of MSW-Income using a spatial panel data approach. We presented the relevant literature and highlighted the main gaps. Among these, we find a general approach for FF and limited use of a spatial framework, despite data evidence. We then approached the problem by dealing with both matters. Thus, we firstly classified FFs and how they may arise in data estimation. We link this approach with interest in tipping points. We used data for total MSW and its sub-flows to understand whether income affects each flow differently and focus on Italian provinces from 2001 to 2018. Socio-economic variables comprise tourism, density, and occupation levels. We treated the model for spatial lags in the dependent, and some independent variables since pre-selection tests and Moran tests underpinned spatial frameworks. The model estimation suggested the absence of any general FF but the presence of varying elasticity. The main reasons for the observed changes are related to spatial interaction, economic activity, and the type of waste. Results suggest that GDP per capita affects the composition of waste flow. Hence, elasticity varies according to waste type and economic variables. We found that economic activity might be relevant in some cases but only at a very low level. In other instances, elasticity varied considerably according to economic activity. Heterogeneity is evident when plotting vulnerability on a map. Elasticity changes over time according to this complex set of variables. Policy instruments in waste management should be applied, controlling for nonlinearity in economic activity and other socio-economic dynamics to avoid undesirable regressive effects between zones. Decentralization might be effective in environmental adjustment as Italy is characterized by a high level of heterogeneity. However, differences in policy instruments to control waste production do not necessarily eliminate the possibility of heterogeneous performances.

We cannot explain whether waste separation positively affects circular policies. It is a *conditio sine qua non* without which material recovery and commodity reuse cannot arise. Nevertheless, some flows seem to reach very low levels of elasticity at low income. Those flows could easily be managed, as they will not change with economic growth. This is a relevant gap that further works might cover.

Our work has shed light on how socio-economic activity might have non-linear effects on waste generation. It offered new ideas in terms of methodology and policy comment. These might be useful for other studies regarding waste sub-flows and effective policies. The necessary step after this work might be to investigate a similar approach to a wider context, such as the EU. We clarified heterogeneity in terms of economic and spatial correlation and how these two interact. Nevertheless, this framework aims to close the gaps by widening the perspective on the income-waste relationship. It is essential to specify the sub-flows to connect with different policy aspects such as climate change, environmental safety, and food waste.

Chapter 4
Strategic resources and in-use stock: addressing the potential material recovery from Electrical and Electronic Equipment

Abstract

This chapter explored the recycling potential across EU28 of Electrical and Electronic Equipment (EEE). This category embodies the commodities that require electricity to function. Per capita endowment of EEE grew from less than 40 Kg in 1980 to more than 300Kg in 2018. The economic intensity of this stock is overall decreasing, and it is currently near zero. EEE is composed of a wide range of materials, comprehending valuables like gold and rare as antimony. We calculated the potential recovery rate of 16 materials from this category. Using inflow-driven analysis, we estimated the potential value for both in-use stock and waste flows. We defined this rate artificial ore grade (AOG), given recycling as mining of the Anthroposphere. Using the same dataset, we estimated the composition of EEE for the same materials and compared the results with other studies. Results show that in-use stock AOG decreases over time, possibly due to the composition change of EEE. Nevertheless, potential recovery from these 16 materials accounts for almost 25% of EEE weight in wealthier countries. Similar results occur for waste AOG. The only two materials that face an increase in rate are iron and chlorine: respectively 0.8%-0.10% and 13%-15% stock-waste. Heavy equipment seems to be the richest category due to the size effect. We finally compared the in-use material stock contained within EEE and the rest of the Anthroposphere. The total weight of EEE is residual compared to the total in-use stock. Our results show that high recovery potential is paired with low material consumption compared to the rest of the economy. This is a good sign for material footprint but negative for the volume of recycled materials.

Abbreviations: Artificial Ore Grade (AOG), Electrical and Electronic Equipment (EEE), European Union (EU), Ore Grade (OG), Waste of EEE (Waste)

Introduction

Material use is a pivotal matter for an industrialized society. According to Social Ecology studies, material use has reshaped manufacturing processes and agriculture since the discovery and use of carbon-energy (H Haberl et al., 2016). The past age's environmental burden has been passed to what Daniel Bell (1976) called the post-industrial society. In this type of human organization, welfare function adds to the classical features of physical, moral, and material satisfaction, the environmental sustainability one. The change of vision has reviewed the constraint of nations. The general way to tackle such matter has been developed by scholars around Europe (and abroad) and crystallized within European Commission policies. One of the objectives pursued by both groups is to substitute linear economy with Circular Economy. The *malus* generated by the so-called "linearity" of the economic system is capable of damaging multiple generations after ours: it is the renounce to "critical capital" as strong sustainability suggests (Neumayer, 2013). The accumulation of not reusable matter under the form of waste can be considered entropy (Kovalev, 2016a). Since we simply cannot reduce disorder generated from economic activity, we can retrofit some parts of waste and reduce the total loss of material consumption. This can partly taper extraction (H Haberl et al., 2016).

The transition to a circular economic model requires an improvement of the level of recycling from spent commodities. Outside packaging and waste food, one of the most relevant commodities are represented by the Electrical and Electronic Equipment, usually called EEE. These are topical for the post-industrial economy as they envelop the digitalization diffusion with computers, the increased welfare level due to refrigeration, light and temperature systems, and so on. The trend of electrification and access to the Internet of Things exists only along with the diffusion and accumulation of such commodities. In terms of policy relevance, European Union has already focused on increasing the circularity due to Critical Raw Materials' presence within their Waste (European Commission, 2017a). As depicted from the Nordic countries, the use of EEE will cause 14% of Greenhouse Gasses emissions for Energy Use by 2040 (Raudaskoski et al., 2019). Therefore, addressing the magnitude of EEE circularity is a crucial aspect of the EU strategy, from waste management to climate policies. In this chapter, we will consider mainly the former. We will address the maximum potential of recycling from EEE. According to the best available technology, this information can help policymakers understand the limit of certain targets for secondary materials.

The objective of making our life-style sustainable must then encompass with particular care for waste from EEE (WEEE). The circularity of such a commodity set could then affect both sustainability and standard of livings. We intend to estimate the aggregate potential recovery rate for materials (for instance, copper, gold, silver) from the in-use stock and EEE waste. We intend the percentage of mass that can be recycled according to a particular technology's performance. We do not focus on the diverse panel of possible technologies, chemical composition, or treatment: the best available technology is applied. We aggregated the results across all clusters of EEE commodities, available time, and nations. We employed the ProSum project results[16], which estimated the stock, WEEE flows, and net stock accumulation for EEE in EU28[17]. Then refer to the work of EU on the review of the directive of 2002 (Huisman et al., 2008) for the literature review of material recovery according to a vast class of elements: Iron, Copper, Silver, Gold, Palladium, Aluminium, Arsenic, Beryllium, Bismuth, Cadmium, Chromium, Nickel, Lead, Antimony, Tin, Zinc, Bromide and Chlorine. We propose to call this general value "artificial ore grade" (AOG); it is a reference index: it will represent the percentage of recyclable metals within the EEE Stock. The "artificiality" is related to the origin of the ore grade (OG) itself, as it comes from manufactured objects. It represents an alternative to the natural one: it consists of the matter that a non-natural reserve can extract. The results are compared then with ore grades citing literature. To test our results' robustness, we compared the compositions estimated with our methodology with in-flow and stock-driven studies on the same materials.

The chapter is structured as follows. The first section establishes the literature framework that influenced our work. We introduce the commodity category of EEE, its denominations and comment on the

[16] http://www.prosumproject.eu/

[17] EU28 is the European Union configuration before “Brexit”. The name is given after Croatia access in July 1, 2013. In other words, it is EU27+UK. The list of European nation contained in this configuration is provided in “Exploring Stock Section”.

distribution according to demographics and history briefly. Calculation methodology follows with the estimation of the AOG: both on waste (reserve) and stock (resource). After evaluating the recovery, we calculated the approximate material composition of EEE. We used such information to estimate which categories are richer of certain materials relative to total stock. We then discussed the results of potential recovery and composition. In conclusion, we provided some examples of the impact of this chapter. We believe that the definition of AOG could foster the taxonomy of urban mining (Johansson et al., 2013), providing methodology, data, and comparison with OG.

Recalling Social Ecology and Environmental Economics: Urban mining

Extraction of resources can generate links to the natural world to the Anthroposphere, also known as the Technosphere. With this term, we refer to the system that embodies both the biophysical and non-physical structure of human society (Baccini & Bader, 1996; Brunner & Rechberger, 2016; Helmut Haberl et al., 2004; Harris & Ayres, 1979). This represents a synthesis of the perspective of social ecology around Material and Energy Flow Analysis (Binder et al., 2013). This definition matters to our study because it delimits the locus where the AOG resides. Indeed, it is possible to evaluate the amount of minerals and metals within the Anthroposphere from many standpoints. In this study, we will consider reserves and resources as located in one deposit. All potential flows that can be extracted by one deposit could be assimilated in one stock: this variable is generally named resource. The difference with reserves stands within the accessibility (Meinert et al., 2016; Otto, 2019). Thus, the amount of available material varies according to technological and economic factors: it can be resource or reserve. We refer to OG as the percentage of material contained within the ore of the deposit. Indeed, this is a generic definition, which is divided into more specific ones. Furthermore, our "deposit" is not either locally isolated or unique. WEEE is collected by every city administration, region, Land, etc. Material recovery could be then affected by spatial networks (Isernia et al., 2019; Messmann et al., 2019). Outside supply chain matters, the definition of AOG could arise multiple interrogatives. For instance, recoverable quantities refer to a fraction of the material composition. Actual recovery is indeed another quantity and can part of secondary materials. Thus, despite the similar use of definitions, they state different quantities. The parallel with OG is useful as it considers the role of technology, price, and availability.

Why AOG

OG represents the amount of metal or mineral in each ton of ore. According to economic feasibility, material composition, and technology, it can be evaluated according to four main definitions:

- Cut-off grade: the minimum metal grade at which an ore-body can be economically mined (used in the calculation of ore reserves); it is used for differentiating between ore and rock (Scholz & Wellmer, 2019; Thompson & Barr, 2014)
- Mill-head grade: metal content of mined ore, which is going into a mill for processing (Mitra, 2019; Roonwal, 2018).

- Recovered grade: actual metal content of ore determined after processing (Ulrich et al., 2019).
- Reserve grade: estimated metal content of an orebody, based on reserve calculations (Ulrich et al., 2019).

Using a flow-driven methodology, commodities are wide and heterogeneous collections identified by digit keys. Thus, the material composition could be estimated but not perfectly known. The composition of commodities within the Anthroposphere is not distant from the reserve grade. The AOG is similar to the cut-off ore grade, given its techno-economic definition. The similarity is useful for making a comparison between artificial and non-artificial OG.

The durability of goods limits the potential extraction within the Anthroposphere, so the amount of current in-use stock should be considered as a reserve. On the other hand, discarded commodities are accessible flows of matter from which materials could be recovered. From this point of view, the main distinction resource/reserve lies between discarded and non-discarded goods. From an environmental point of view, there has been a concern for reducing ore grade of extracted materials (Calvo et al., 2016; Rötzer & Schmidt, 2018; Ruberti & Massari, 2018b; Yellishetty et al., 2010). This pattern may refer to the introduction of new technologies. With these innovations, available resources increase rather than reduce (Rötzer and Schmidt, 2018). Despite the common fear, the link between available technology and available resource is generally positive.

On the other hand, transformation stages through the material cycle generate dissipation. Thus, innovation in extraction may not be enough to counter this effect. As previously said, retrofitting part of used materials can partially save from dissipation. We considered ore grade effective in defining where and how certain quantity materials were possible to find within the Anthroposphere.

Reference Literature

The chapter bridges many streams of literature: material flow analysis, recycling technology, and mining economics. The first one relates to economy-wide inflow-driven stock analysis. This field of research aims to quantify the flows directed and stock accumulated within an economy. Inflow-driven methodology treats flows as exogenous, estimating the stock within a system as the sum of variation over time (Fishman et al., 2014; Krausmann et al., 2018). The model sink is estimated via deployment function (Wiedenhofer et al., 2019) or using data on waste (Krausmann et al., 2018). The deployment function consists in a distribution function of the durability of commodities within the in-use stock (Miatto et al., 2017). This function is a cumulative distribution function with an average timespan and constant variance. Furthermore, it assumes that the durability of commodities is normally distributed and stationary over time. Another distribution fairly used is the cumulative Weibull (W). As with any cumulative distribution, its maximum point is 1. The data we employed used a Weibull cumulative density function of such form:

$$W(t,\lambda,k) = 1 - e^{-\left(\frac{t}{\lambda}\right)^k} \tag{17}$$

The parameters λ and k are respectively shape and scale: they define the average durability, skewness, and kurtosis of the distribution. We will not comment here on the characteristics of the Weibull distribution. The decaying function is related to the accumulation cycle of commodities in a reference system. The stock (S) variation is equal to net addition (N) times a decaying factor.

$$\dot{S} = (1 - W_t)N_t \tag{18}$$

Net additions are composed by the number of commodities produced within the system plus the imports and minus exports. The quantity multiplied by the decaying function is equal to the substitution. The model does not focus on the direction of this flux. The second approach is called stock driven. In such models, the stock is conceptualized as consisting of cohorts of service units with specific material compositions. For example, vehicles or buildings of different ages are ordered in classes or cohorts (Wiedenhofer et al., 2019). Data is revealed throughout surveys or statistical estimation. The use of deployment functions, also on inflow models, is a characteristic of the stock-flow model, where outflows are endogenous to the durability and average use (Müller et al., 2014; Schiller et al., 2017). Data used in this chapter follow both methodologies. Since placed on market data and Waste from WEEE are both existent after 2001, previously generated data is estimated. The stock reaches a maximum point when net additions are employed only for substitution i.e., when W = 1. As data on stock and waste became available from 2001, top-down methodology defines the stock; before that moment, the authors used the bottom-up approach to estimate the stock variation. Other works have analyzed the potential recovery from EEE. Outside exemplar technical studies (Lennartsson et al., 2018; Vermeșan et al., 2019), many works have dealt with this matter, focusing on few categories or certain minerals or metals. A great interest towards WEEE and recycling is the economic potential (Charles et al., 2017; Ueberschaar, Otto, et al., 2017; Ueberschaar, Schlummer, et al., 2017), limits (Andersson et al., 2019; Ueberschaar, Schlummer, et al., 2017), and economic driver study (Kusch & Hills, 2017). Indium and gallium in WEEE recycling (Andersson et al., 2019, Ueberschaar et al., 2017), where extraction seems to be difficult due to marginal quantities and costly technologies. Nevertheless, economic growth is a good predictor of WEEE growth (Kusch and Hills, 2017) and recovery. Work on urban mining has estimated that WEEE is the second biggest source of copper in the anthropogenic cycle (Ciacci et al., 2017). We believe that our study results generate two main outcomes: a wide perspective on potential recycling of WEEE across three dimensions. The first one is a geopolitical dimension of EU28. The second refers to the number of elements we considered. Then we considered a large group of elements.

Exploring the stock

EEE is a collection of heterogeneous commodities that can be grouped according to various commodity indexes. Each databank has its classification methodology. For instance, ProdCom[18] (PC) and United Nation University (UNU) adopt a different key system. Similarly, the EU adopted two categorizations for waste. Chronologically the first one was EU-10[19] with ten groups of commodities while EU-6[20] the second with 6. The 2002/96/EC directive, effective from February 2003, established the former system. The 2012/19/EU directive prescribes the latter classification. Since the ProSum project matched the codes, it is possible to use a smaller number of categories such as EU-6 or EU-10 to synthesize EEE in 6, 10 groups instead of 52 (UNU), PC (100+). This parallelism will be useful in this section and in the methodology section. As plotted in figure 15, the EEE stock has had a constant increase in weight since 1980. From an estimated value of 3272931 tons across the current 27 states of the EU plus the United Kingdom, it jumped to 274008495 tons. The end is almost 38 times the start, demonstrating the immense material consumption in the last forty years. The average growth has been around 9.5% yearly. The general trend reduction can be imputed by stabilizing growth and stock replenishment, which affected mostly light-weighted objects. According to project calibration, large equipment tends to have a larger lifespan with respect the others. This could be the reason for thespecific drawbacks of small equipment and IT. The figures per capita change dramatically.

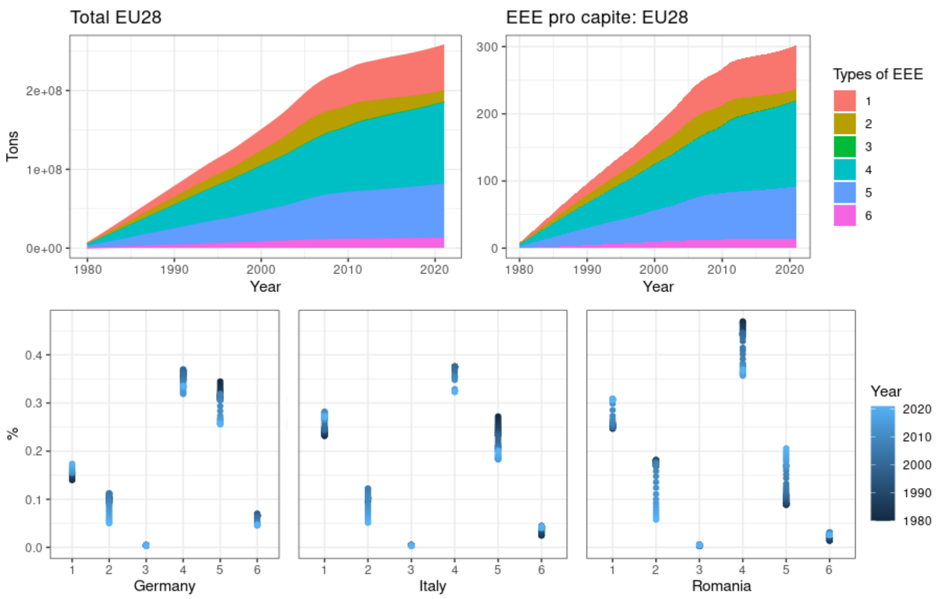

Figure 15: Total stock of EEE in EU, data from PROSUM, EU-6 classification: 1 (Temperature exchange equipment), 2 (Screens, monitors, and equipment containing screens), 3 (Lamps), 4 (Large equipment), 5 (Small equipment), 6 (Small IT and telecommunication equip

[18] ProdCom ("PRODuction COMmunautaire" from French) is the databank that registers manufactured products sells. Quantity of items, average price and weight are listed.

[19] EU-10 WEEE classification encompasses commodities of these categories: Large household appliance, Small household appliance, Telecommunications and IT equipment, Consumer equipment, Lightning equipment, Electrical and Electronic Equipment, Toys, leisure and sports, Medical devices, Monitoring instruments and control, Automatic dispensers.

[20] EU-6 WEEE classification: Temperature exchange equipment (TEE), Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2, Lamps, Large equipment (any external dimension more than 50 cm), Small equipment (no external dimension more than 50 cm), Small IT and telecommunication equipment (no external dimension more than 50 cm)

The EU28 dweller in 1980 owned on average 40 Kg of EEE stock. The small stock dimension was related to larger family composition, lower purchase power, and inequality across EU nations due to the Iron Curtain. Thus, large appliances were shared by many individuals, while other small devices while generally rarer. On the other, the EU citizen of 2020 has access to an estimated 300 Kg of EEE. The drastic change could be motivated by two causes. The increase of population might be one; the average basket of commodities increased. EEE stock is composed of a variety of commodities that changes in weight and composition over time. To have a synthetic perspective on the in-use stock, we traced the UNU-Keys to the relative waste classification EU-6.

The stock of in-use EEE is available with clustering at the national level for 28 countries and EU members. Within figure 16, we presented the quantity per capita, according to three classes of purchase power:

1. Above 35.784 Euros: Austria, Netherland, Ireland, Sweden, Belgium, Denmark, Germany, United Kingdom, Finland, France, Luxemburg
2. Between 23.068 and 30.289 Euros: Spain, Slovenia, Cyprus, Czech Republic, Malta, Portugal, Slovakia, Italy, Greece
3. Below 23.068 Euros: Poland, Hungary, Estonia, Croatia, Lithuania, Latvia, Bulgaria, Romania

The division in "*strata*" is useful to underline the differences in recycling potential across the EU and UK. Since the PP affects EEE accumulation and waste generation dynamics, it seemingly affects the recycling potential.

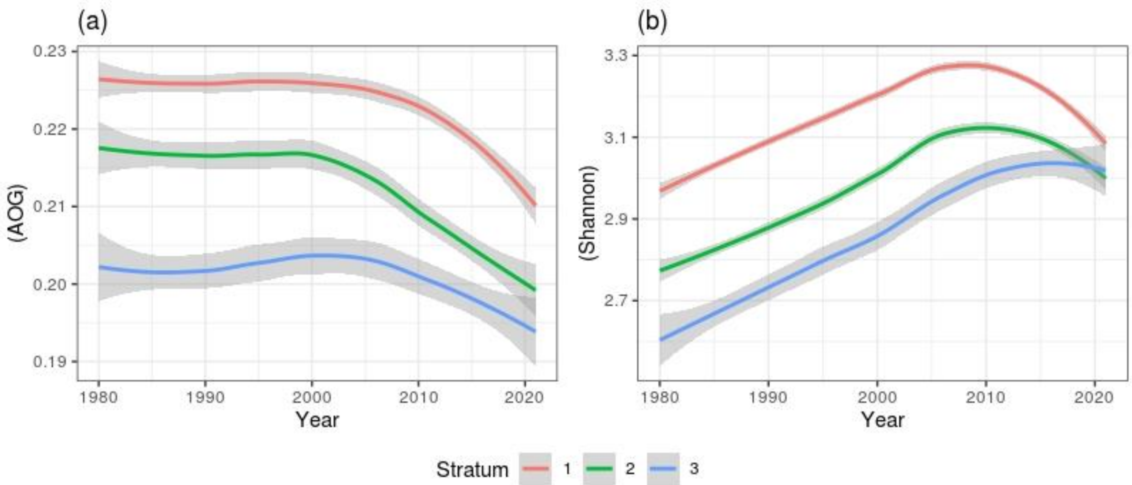

Figure 16: (a) EEE total AOG and (b) Shannon Concentration Index

The small commodities reduced the accumulation rate after a faster path during early 2000. On the other hand, large equipment growth almost linearly since the start of the panel. For these two categories, the difference in weight exists for the trends too. Finally, temperature exchange commodities have reduced trend around 2008. We took as an example of change within the panel Germany (*stratum* 1), Italy (*stratum*

2), and Romania (*stratum* 3). Considering the proportion of quantities within the stock, strata 3 countries tend to have a higher proportion of heavy equipment (4). This category contains freezers and washing machines. On the other hand, Small equipment had a rapid growth. This category contains fans, radios, etc. The other two *strata* tend to be more stable in changes.

The composition of such stock has dramatically changed between 1980 and 2020. Consumers and firms could access various new functionalities, from personal computers to recent phones and television. Differentiation could be measured with an index of concentration. We used the Shannon index H. It indicates how small the parts that compose a set are.

$$H_{nt} = -\sum_{\forall i} M_{int}/M_{nt} ln(M_{int}/M_{nt}) \tag{19}$$

Values of such index are calculated per year (t) and nation (n), and commodity type (n). The value of the index H contains the negative of portions times the logarithm of portions. Each portion is calculated as a category to the total EEE mass ratio. Equation 19 has interesting properties to us. The natural logarithm is negative when the object is below 1. Thus, H grows when the distribution of proportions flattens. In our case, it is possible to see that distribution was generally more complex in higher *strata*. Between 2000 and 2010, we registered convergence in values. If our results reflect well real dynamics, on average, Europeans have similar EEE baskets in terms of concentration/complexity.

Methodology

The available information at disposal contains a set of percentages of recovery. This value is matched according to the category of waste (EU-10 in this case) and the recovery element. We call this a technology matrix of "n" commodities and "m" materials, where "n" and "m" are integer numbers. We used a unique matrix of technology due to the impossibility of adding further layers of time. Possibly, in case of finding additional results or changes in this technology matrix, the number of technology matrices could change per year. The perspective that we can use is nevertheless useful according to the point of view. Considering this a "state of the art", we can consider the potential recycling of past commodities according to our time: you would choose the best technology at hand. Indeed, the technology has developed since 2008, but literature has not yet developed uniformly per each material.

The data set on which we intend to apply the technology matrix is the stock and waste panel data for the twenty-seven plus UK states of the Union. Using the parallelism of EU-6, EU-10 waste indexing to UNU-keys for panel indexing, we matched the panel data's technology matrix. Using the assumption of technology implementation, we have three assumptions:

- Point of view: the technology matrix must refer to the available technology at the current moment.
- Perfect transition: no dissipation occurs in the collection.

- One for all: every nation has access to the same level oftechnology.

The assessment we intend to produce is to mix two branches of literature on industrial ecology. One is the material flow analysis; the other relates to recycling studies. By combining the available technology for recycling (hereby-called technology matrix, due to its materials versus waste category structure) with the EEE stock, we estimate the maximum possible AOG per nation, time, and material. A synthetic definition to identify the available level or recoverable resources of an element "m". It is calculated as a value between 0 and 1, for a year "t" and extracted from a commodity "n". In our model, we considered flow M_{nt} per each country and then the in-use stock of EEE S_{nt}. The flow could be waste-based "W" or in-use "POM". The technology matrix w_{mnt} matches the flow of waste or in-use commodities. It represents the interaction between the material composition and recovery potential of the metal. A

$$P_{mt} = \sum_{\forall n} w_{mn} M_{mnt} \tag{20}$$

composition matrix is provided by Eu commission estimates (Huisman et al., 2008). The recovery potential is constructed following estimates found in a literature review (Awasthi & Li, 2017). The potential recycling for each material equals the linear interaction between material flow and w_{mn}. According to the nation, this index's comparability requires a relative value according to the total flow or stock we are considering. For instance, if applied to waste generation:

$$g_{mt}^{W} = \frac{P_{mt}^{W}}{\sum_{\forall n} W_{nt}} \tag{21}$$

According to stock potential:

$$g_{mt}^{POM} = \frac{P_{mt}^{POM}}{\sum_{\forall n} S_{nt}} \tag{22}$$

The accounts necessary to estimate the flow-stock models are derived from Eurostat's international market entries and market sales. The net addition to the market is then moderated by the flux exiting the system under the definition of waste or WEEE. As in a thermodynamic system or a macro-economic model, these entries determine the relation between the in-use stock and the rest. The main nomenclatures are defined as PRODCOM digit keys, which are specific categories in which commodities' fluxes (value and number of items) are registered. The nomenclature links to the second stream of data. It comes from the field of industrial ecology and recycling management; here, we collected data from literature about the evolution of recycling technology currently available. These fields use a different digit key system for waste flows, consistent with the EU waste directive for EEE. Results from recycling management usually refer to ten categories of WEEE, called EU-10. A similar classification is the EU-6: both represent a set of categories of collected WEEE.

On the other hand, Eurostat keys for EEE commodities overcome seventy entries. To solve this inconvenience, we traced the nomenclatures of in-use commodities within the waste registry and created a small dataset for comparison. This stream calibrates the value for the technology matrix w_{mnt} by linking the stock of EEE with recyclable mass, using WEEE nomenclature. Since definitions are almost static but always unequivocal, each UNU key flow is simply the sum of PRODCOM keys flow. Similarly, we can say about EU-6/10 and UNU keys, with the difference that one category expresses non-use stock (waste), while the other in-use stock. Since we cannot precisely determine the potential recovery of each UNU key, we will stick with generalist interpretations. The AOG will represent the potential recovery for the whole basket of commodities within EU-10.

Results

Table 8: Results of ore grades by Stratum: (U.S. Geological Survey, 2018)1, (Ruberti & Massari, 2018a)2, (Schulze & Buchert, 2016)3, (Eilu, 2012)4, (Rötzer & Schmidt, 2018)5, (Tornos, 2006)6, (Leistel et al., 1997)7

Elements	OG	1	2	3
Iron	30–60 % 1	[5.45,6.82%]	[4.84,6.49%]	[4.3,5.83%]
Copper	0.5–3 % 1	[7.57,9.52%]	[7.27,9.55%]	[6.93,8.86%]
Silver	265 g/t 2	[0.013,0.029%]	[0.013,0.026%]	[0.012,0.030%]
Gold	1.5–15 g/tonne 1	[31,44.1g/t]	[27.2,43.7g/t]	[25,53g/t]
Palladium	0.01063-6.16 4	[17.2,23.7g/t]	[15.8,23.2g/t]	[14.9g/t,29.3g/t]
Aluminium	30% 5	[3.64,4.82%]	[3.5,4.84%]	[3.33,4.22%]
Arsenic	0.34-0.43% 6,7	[0.15,0.331g/t]	[0.063,0.423g/t]	[0.118,0.471g/t]
Beryllium	0.265-0.8 % 3	[0.279,0.616g/t]	[0.118,0.787g/t]	[0.22,0.878g/t]
Bismuth	NA	[13.8g/t,74.2g/t]	[14.8,68.5g/t]	[14.6,69.8g/t]
Cadmium	0.3%-0.5% 1	[0.009,0.0196g/t]	[0.004,0.0251g/t]	[0.007,0.028g/t]
Chromium	30% 7	[0.011,0.018%]	[0.006,0.021%]	[0.008,0.022%]
Nickel	0.5–2 %	[0.060,0.0916%]	[0.0516,0.0903%]	[0.0485,0.116%]
Lead	1–15 % 1	[0.524,0.804%]	[0.501,0.77%]	[0.447,0.71%]
Antimony	14% 3	[0.020,0.043%]	[0.019,0.0359%]	[0.018,0.0398%]
Tin	0.3–1.5 % 1	[0.665,0.923%]	[0.634,0.899%]	[0.579%,0.844%]
Zinc	1.5–12 % 1	[0.762,0.947%]	[0.738,0.945%]	[0.684%,0.862%]
Bromide	20 – 30% 5	[0.057,0.167%]	[0.054,0.147%]	[0.058,0.192%]
Chlorine		[0.059,0.088%]	[0.046,0.116%]	[0.029,0.060%]

Following the assumption of the point of view, we collected in intervals the values of the AOG. In such a manner, we can relax the determinism of interaction between technological matrix and composition in a static way. We elaborated a specific analysis within the additional section, dividing the materials into classes. Classification of these values has been made for percentage or part per million (g/t). To compare the OG values, we collected a group of articles most cited on minerals report and other cited articles. The results show that WEEE is relatively richer in precious materials such as copper, silver, gold, and tin than natural stock. Despite the relative richness of Iron within the anthropogenic stock, its AOG is not comparable to its natural counterpart. Except for Lead, other materials in our panel possess relatively insignificant recycling potential. This estimate does not state the economic inconvenience of recycling. It nevertheless fits previous works' results (Chancerel et al., 2009; Charles et al., 2017; Messmann et al., 2019). Our results show that despite composition is one of the main drivers of recovery; the size effect is not still relevant. Iron is the most common of materials. On the other hand, lighter elements such as copper are easier to recover, thus present a higher AOG. The comparison with OG is impressive when considering the ages of some materials. Copper, for instance, is at the same time easy and common within WEEE. Elements such as Copper, Tin, Gold, and Silver are relatively more common in the Anthroposphere. Indeed, this is not always true since ore grade and abundance are inversely correlated (Rötzer & Schmidt, 2018). We know the "resource" structure as it coincides with the in-use stock of EEE. Therefore, the exploration problem resides mainly within the extraction technology. The best available technology has the property to reduce the distance from resource and reserve.

Composition, potential, and actual recovery are distant in terms of feasibility. For instance, potential recovery must be weighted with waste management and other losses during the recovery cycle. On the other hand, the composition of commodities tends to vary across time. A similar aspect could be said about weight, which is, on the other hand, yearly estimated for all commodities of EEE. The weight of plastics, rare materials, and other metals within commodities has changed.

To investigate in which commodity groups reside each class of materials, we calculated the material stock R_{ht}. The index h refers to the waste classification EU-10. The stock of commodities Sh can be arranged according to index i or h when summing. The concentration c_{ht} is based on estimations made on waste samples of EU-10 categories. So, the estimated material stock is calculated according to the EU-10 classification. We then calculated the weight p_{ht} by dividing by the sum of total potential at each time.

$$R_{ht} = c_{ht} \sum_{\forall h} S_{it}^{h} \tag{23}$$

$$p_{ht} = \frac{R_{ht}}{\sum_{\forall h} R_{ht}} \tag{24}$$

From equations (23) and (24), we estimated the commodity distribution of commodities. In other words, we can understand in which waste categories some materials are concentrated. We choose Italy as an example. It is a *stratum* 2, the third Eu nation for demography altogether with a sizeable manufacture structure. We plotted the most common metal (Iron), two precious metals (gold and silver), and a rare element (Antimony). Given relative growth within the stock, large household equipment and IT are rich for all four materials. This is due to the increasing presence of such stock categories within the commodities basket, as shown in Figure17. Since estimates had been made in 2013, we assumed that variability of commodity composition affects the certainty of this weight before 2000. Nevertheless, results in recent years appear consistent.

To test our results' validity, we summarized in Table 8 the general results compared to known examples in literature. We calculated the composition of materials according to the EU report on WEEE. The results show that materials contained within EEE represent a small proportion of the overall in-use stock composition. The year of reference for our results is 2012 when cited literature is focused (Pauliuk et al., 2013; Pfaff et al., 2018; Rauch, 2009; Sverdrup et al., 2014). For instance, iron in EEE represents on average 1% of the total in-use stock of iron. Copper and silver contained in EEE compile for less

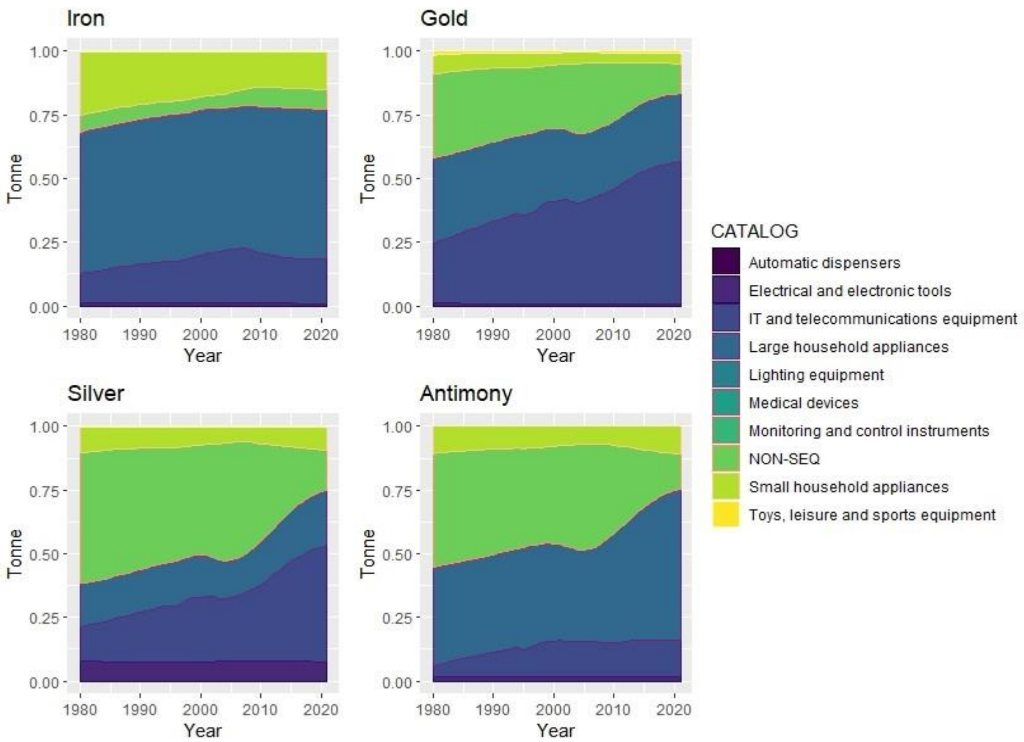

Figure 17: Resource AOG, which categories of EEE contain Iron, Gold, Silver and Antimony

than 6%. Aluminum less than 5%. Considering the impact that such commodities have on our welfare, the EEE material footprint is residual compared to the rest of the economy.

Discussion

The results show a slight reduction of the AOG after the decrease of the Shannon index. Our model behaves apparently as the natural one (Calvo et al., 2016). Changes in AOG are mainly driven by the difference in the composition of the basket. Furthermore, since this is a mere potential evaluation, we need to focus on time. Changes in ore grade took centuries, if not millennia, to take place. Material cycles are faster within the Anthroposphere, considering the heterogeneous and limited durability of commodities. Given these results, it is probable that recycling is more dependent on innovation ceteris paribus and is affected by the composition of in-use stock compared to mining. Of course, both values of material commodities and the increasing rarity of materials tend to drive innovation (Stürmer & Schwerhoff, 2012).

From the perspective of urban mining, EEE seems to be a rich locus of extraction. Total potential recycling is still higher than 20% of the total weight across the EU. This estimation does only contemplate considered elements. This study does not consider packaging or plastics. There exists the possibility for improvement. It is necessary to underline the importance of commodity durability and potential recycling. When considering an in-use stock, it is more common to trace materials in long-lasting commodities: they appear as a rich reserve since they substituted less. On the other hand, less durable commodities will appear richer from the waste perspective, for the opposite reason of the previous category. It is not clear the effect that durability has on the total benefits of circularity for EEE. Reduction of lifespan may induce increases turnover of commodities, and thus materials consumption. On the other hand, it affects the flows of potential recovery.

The mass balance between Anthroposphere and ecosystem can be aided by material circularity. Still, understandings of the relation between stock composition, welfare, material consumption, and recovery can be improved. Furthermore, the materials that reside within the EEE basket represent a minor share of total in-use stock. Thus, every sustainability issue related to this stock must be weighted to the proportions highlighted above. The complexity of the stock is related to the relative in-flows of new commodities. This is related to imports and inner production. Such flows are in part directed to the international markets. We believe it is related to the level of complexity that an economy can reach. The level of information complexity that EEE gathers is one of the highest according to the Economic Complexity Index (ECI). The capability to accumulate, produce and reuse or recycle this flow is therefore strategic. In terms of economic feasibility, it is Pareto efficient to reuse or recycle EEE only for similar or better purposes (Pothen, 2013).

The AOG is useful to understand the real trade-off between in-use commodities. For example, heavy equipment stock can be materially substituted by a larger quantity of smaller equipment. An economy enough complex can sufficiently diversify the stock of EEE and the proper technology to recycle it. Thus, the recycling potential would increase. As our results have shown, PP is generally a predictor of higher AOG, diversity in stock increases in PP. Besides, ECI is a good predictor of PP (Hausmann et al., 2014). At last, the results of composition analysis underlined the low material consumption of EEE. This is particularly useful for the material circularity of EEE, as they could require low mass flow from other in-stock categories.

On the other hand, the recycling mass volume is not high, explaining the reason to search for aggregation and supply chain network (Messmann et al., 2019). The volume of mass and rate of recovery is indeed a typical characteristic of ore grades. In case it could be found similarly for other Anthropospheric categories (for instance, the potential recovery of metals from buildings, clearly higher mass), the AOG would represent a fit definition for this indicator.

Conclusion

The research has produced two main outcomes. One related to potential recovery that we defined as AOG. The second is an estimation of the material composition of EEE for the sixteen materials. We collected the results in two different data sets. The first dataset interpretation appears technologically feasible to reuse more than 22% of the total weight of in-use stock and around 20% of waste according to available technology. We used state of the art in calculations; thus, technology innovation is not the main driver of change in time. We think the change is indirectly related to socio-economic factors and the limited life span of commodities. If we consider EEE as a potential mining field on a large scale, we register high ore grade, compared to the four-definition used in literature. On the other hand, the AOG cycle seems to be faster than ore grades from mining extraction. We believe this trend will stabilize either with technological change or with the stabilization of EEE stock. Thus, in the long-run, the recovery potential and lifespan of commodities will be entangled. Furthermore, despite its potential, EEE stock represents a small fraction of overall in-use stock, i.e., the nation's weight. We employed for this analysis the second dataset.

For further studies in economics, we highlighted no need to invest in exploratory technology in urban mining. Reserves are known to be the composition of commodities. Therefore, the main interests should be placed into recovery technologies. In a Circular Economy setting, these have the property to reduce the distance between resources and reserves. Overall, modeling the impact of circular innovation towards stock recovery has interesting policy impacts. While innovation increases recovery, the impact on EEE or other stock accumulation is unknown. If it increases, there might be proof of a weak relation between economic development and circular innovation. Furthermore, waste policies that increase the recycling potential could affect the accumulation patterns. This research gap has not been previously analyzed.

We believe that the definitions and data we produced can positively impact both social ecology and environmental economics. For the first one, our composition results display synthetically where and how much materials are present within the EU Anthroposphere. It is relevant to economics since it adds composition effects to potential recycling. The results can be evaluated within a policy framework. The results of this research are in the end partial, considering that we focused on a narrow set of materials. Furthermore, this approach could be applied to other flows or stock, such as buildings, infrastructure, and vehicles. These are wider and thicker categories concerning EEE. In this way, it would be possible to measure the potential weight recovery of nations.

Chapter 5

Material Governance and Circular policies: how Waste Policies affect Household Appliances' accumulation

Abstract

Circular Economy requires a great effort in monitoring material flows, market dynamics, and policymakers' perspectives altogether. Here an attempt is made to understand the macro-economic perspective of accumulation when circular policies are in place. The application is made on the Electrical and Electronic Equipment of household appliances. This category is relevant due to the EU commission's specific effort to tackle the Circular Economy and material accumulation of critical raw materials. To understand the optimal dynamic of accumulation, innovation, and recycling, we developed a two-stage work. The former is a theoretical model of growth. A social planner establishes in a closed economy the optimal selection between generic consumption and net material addition to intertemporal welfare. A capital and a material stock are then used as input to production. Material recovery is applied to the discarded commodities from the material stock and reused as a factor of production. Innovation is created via specific investments and piles up as an immaterial stock affecting productivity. This framework is used to delineate the biases of a panel data model. To counter such a problem, we applied a feasible generalized least square. Economies are interlinked and cross-sectional dependence in material accumulation persists. Variables used comprehend structural, socio-economic, and intrinsic characteristics of EEE stock of EU27+UK panel. As intrinsic, the panel uses average-timespan, weight per capita, and Shannon index of concentration. The dummies for EU waste packages of 2008 and 2012 are used to control for policy breaks. The results show high significance among the general application and within each income class. Waste policies are strongly correlated to an increase in material accumulation rather than a reduction. Socio-economic variables are generally significant, with evidence of decoupling. Lastly, the timespan is positively correlated to material accumulation. The results highlight the strong significance of policy effectiveness to economies' material dimension, even at concluded economic cycles.

Abbreviations: Electrical and Electronic Equipment (EEE), feasible generalized least squares (FGLS), Environmental Kuznets Curve (EKC)

Introduction

Circular Economy is an umbrella definition for the vision, policy framework, and business models that disregard waste and use virgin materials (Homrich et al., 2018). For the European Union, it is a policy nexus for the transition to a more sustainable society. Circularity is linked to different issues: sustainable development, trade security, economic growth, and innovation. The environmental ones are related to the sustainability of our lifestyle. The strategic ones are related to protecting our industrial assets despite external pressure of political instability and trade disputes. The former refers to the better use of resources in a fair society that should lead to a better tomorrow. The latter one touches on the dependence of green and technological innovation on a set of strategic materials. Electrical and Electronic Equipment (EEE) represents a relevant class in both terms. For our system's sustainability, they synthesize most human welfare functions in a limited set of commodities. Therefore, keeping utility constant, electrification reduces material consumption (Pearson, 2013). The circularity of EEE is topical for European Union Objectives. At this point, we need to cast a clear difference of what we define as circular. A commodity that overcomes its role and is due to discarding should be considered as a resource. Developing sectors that recover discarded EEE and their materials are not part of the Circular Economy *per se* (Homrich et al., 2018).

The objectives of the European Union regarding EEE could be summarized according to the waste policy package in 2017 (European Parliament and Council, 2017) and the communication on circularity "Closing the Loop" (European Commission, 2015). Sustainable development passes through better use of current resources, improved recycling and secondary materials, and circular innovation. While studies on innovation and sustainability have generated a prolific field of study, the impact on the recovery and accumulation of commodities is still relatively unknown at the macro level. We will therefore study the impact of circular innovation on the material accumulation of EEE. In the previous chapter, we have presented the impact that economic development had on waste generation and how waste was dramatically reduced after introducing EU policies. It is still unknown if this affected the dimension of the in-use stock of EEE. If products are discarded less, they are probably used more and more efficiently, increasing global efficiency. Recycling has been growing, and attention toward the recycling of waste of EEE has constantly increased globally.

We will divide the chapter in this way. A concise literature review will shortly present three strands of literature. One relates the definition of the Anthroposphere and its material dimension. The other is the theoretical models of materialistic relations within an economy. The latter describes the applied models that underpin the hypothesis of economic cycles and the endogeneity of material dependence. A methodological section takes place further. It is split into a theoretical model and then an applied statistical one. The theoretical model has the objective to present a dynamic relation between innovation, recycling, and economic growth. Its purpose in this study and future research is to link the applied model to the policy framework, motivating variables, and statistical tests. To introduce then the applied section, we will present a data section. The results and the regression model are explained later in Results. We will explain the impact of such findings on material circularity in the discussion. Lastly, the conclusion will summarize the innovation proposed by this work.

Literature

Our work uses notations and definitions of different branches of resource economics modeling. We aim to link the exogeneity framework of inflow-driven mass equilibrium and economic modeling. The latter has used data estimated from the former methodology to assess decoupling and policy effectiveness (Bringezu et al., 2004; Krausmann et al., 2009; Steger & Bleischwitz, 2011; Wilts & O'Brien, 2019). Inflow-driven assessment assumes that the economy's net addition is endogenous to new product acquisition and natural decay of stock (Fishman et al., 2014; H Haberl et al., 2016; Wiedenhofer et al., 2019). This factor is assumed to vary according to time: as time departs from the start, the substituted stock proportion tends to one. When substitution factors converge to one, all net addition are devoted to substitution; hence the material stock is considered mature (Bleischwitz et al., 2018; Winning et al., 2017). Despite common purpose, this approach is relatively rare to find cited among economics works. Nevertheless, we think it is relevant for material circularity modeling.

Policymaking mainly relies on economic indexes such as Gross Domestic Product (GDP) to evaluate economic performance (Stiglitz et al., 2018b). This is relevant to evaluate ex-post policy results, especially in mainstream environmental economics (see Environmental Kuznets Hypothesis). We believe the division Anthroposphere vs. Geosphere nexus (Zoboli, 2019) allows us to expand the number of scientific instruments. One is the material mass of an economy (Matthews et al., 2000) and its circularity (Zotti & Bigano, 2019). This is a valid alternative for Circular Economy studies as it pictures the material scales in a universally understanding. Weight does not inflate or deflate sensibly. A second one is the complexity of such stock in terms of stakes of different in-use commodities.

We will review Circular Economy models that are based on green growth. In such models, the planner maximizes utility as in others. Although beneficial, consumption leads to pollution, which damages utility. As in the green Solow model, economic activity is used to increase welfare from consumption and financing pollution abatement (Brock & Taylor, 2010; Stefanski, 2010). Such an approach is used to underpin Environmental Kuznets Curve (EKC). According to this approach, reduction of pollution appears in two phases: relative and then absolute decoupling. This literature affected the branch of Circular Economy to recover part of the pollutant/waste. Circularity as recycling modeling is divided into renewable and non-renewable approaches to the growth model. Hotelling approaches are generally employed for a limited horizon (Cynthia Lin & Wagner, 2007; Hotelling, 1931). The material balance equation (Ayres, 1995) is required to follow the second law (Bryant, 2015; Georgescu-Roegen, 1971; Krysiak, 2006). The growth model is generally used in a neoclassical context of utilitarianism (Di Vita, 2001b, 2001a), particularly for tax effect on recycling of renewable resources (Di Vita, 2004). In such cases, recycling increases material extraction, inducing higher rates of economic growth. For non-renewable resources, there are similar results if perfect substitution of manufactured (or recycled) and natural capital is assumed (Di Vita, 2007). When this condition does not apply, equilibrium is sustainable only for Hick's neutrality, i.e., innovation is unbiased (Comolli, 2006). Application of circularity could be intended as pure materialistic models (without labor or innovation), where the main interest is to decouple waste, considered as pollution (George et al., 2015).

Innovation is used in finite and infinite horizons. For the second one, introducing a recycling policy is strongly related to the level of consumption of exhaustible resources (Lafforgue & Rouge, 2019). Innovation and knowledge level affect either pollution abatement (Chu & Lai, 2014) or/and recycling rate (George et al., 2015). Despite our best effort, no level of technology might allow us to recover materials perfectly. The accumulation of useless materials could resemble a reference to the physical concept of entropy (Kåberger & Månsson, 2001; Kovalev, 2016b).

Considering primary and secondary materials as almost perfectly substituted, innovation in recycling works as in mining. In such a case, increasing yield of extraction could be achieved even at lower ore grades (Stürmer & Schwerhoff, 2012). Such assumption is relevant only when considering the material composition of commodities rather than homogeneous and linear products as assumed in the literature. Previous studies focused on material composition commodities assuming mostly supply-side drivers, such as aluminum prices in cars (Kandelaars & Van Dam, 1998; Roberts, 1992). We intend to apply a demand-side approach from resource economics to test the possibility of demand-side drivers in EEE material composition. To explain the theoretical premise of this chapter, we will now present a simple macro-economic growth model.

Methodology

Accumulation and circularity in theory

Our theoretical model is an inter-temporal optimization. A social planner chose a quantity of consumption "C", the new addition to material stock "N", and R&D circular innovation expenditures "F". Retrofitting commodities for secondary uses (from recycling to recovery) could cost. For simplicity, we will assume that the circularity sector is endogenous to the economy and only net additions N costs to the system. In other words, social planner pays for net addition, technological development for recycling but not the cost of secondary flows. Such variable is collected in the sector of recovery $R = gdM$. In this case, we will set unitary costs "p" to be constant for simplicity. In such an economy, investments "I" are allocated to capital substitution δK, F, capital variation, and net material additions. They equal disposable income (equation 25).

$$Y_t(R, M, K) - C_t = I = \dot{K}_t + F_t + \delta K_t + pN_t \tag{25}$$

Expenditures in technology are proportionally accumulated into a stock of technological stock B in equation 26. We presumed that this rate of accumulation was deterministic and linear. The value of the parameter η determines the success of investment policies in generating the stock B: lower values of such parameter indicate greater efforts to be made for circular innovation. The purpose of this stock is to increase the recovery performance "g":

$$\dot{B}_t = \eta F_t \tag{26}$$

Recovery performance is taken from climate change literature, as abatement technology cannot fully achieve perfect recovery. In this sense, the maximum potential of recovery is always lower than unity. In the previous chapter, we consistently found that this feature is present in EEE potential recovery, with the definition of the Artificial Ore Grade. This concept was also chosen to resemble the constant growth of entropy in environmental models. The accumulation of useless "work" could be a trace in the cumulative distance to perfect recovery. We assumed that such a limit is equal to “a,” as explained in equation 27.

$$g_t = a - e^{-bB} \rightarrow \lim_{B\to\infty} g = \mathrm{a} \tag{27}$$

Altogether with technological stock, the economy accumulates a material stock “M”. Its variation is the function of new additions and material decay. Despite the desire for material acquisition, stock M grows until maturity, where new additions are used only to substitute old units. Since treating waste generates hazardous materials, all non-recycled commodities generate dis-utility according to $(1-g)dM$.

$$\dot{M}_t = N_t - dM_t \tag{28}$$

$$U = U[C, (1-g)M]$$

$$gdM = R$$

In this system, income is generated using three main inputs: capital K, material stock M, and recovered stock R. We assumed that R is equal to discarded material stock “dM” multiplied by recovery rate “g” as presented in group equation 28. In such a way, it is possible to see that using two times affects general productivity. It could resemble either secondary material or recovered components. Since this model intentionally overlooked market values, we ignore the differences. In terms of weight accounting, it does not differ. We rewrote production function as simply Y=f(K,M). Productivity is then composite of an exogenous factor and an endogenous one. To simplify at this stage calculation, we assumed “d” to be implicit; we will recall later how commodity durability affects macroeconomic equilibrium.

$$Y_t = \varepsilon_t K_t^{\alpha} M_t^{\beta} (g_t dM_t)^{1-\alpha-\beta} = K_t^{\alpha} M_t^{1-\alpha} \left(g_t d\varepsilon_t^{\frac{1}{1-\alpha-\beta}} \right)^{1-\alpha-\beta} = \epsilon_t K_t^{\alpha} M_t^{1-\alpha} \tag{29}$$

Our economy will have the purpose of increasing welfare by acquiring new commodities and regular consumption. The first value is relevant for accessing new functionalities, such as medical and personal utility. Despite the possible criticism over its venality, the Anthroposphere requires constant upkeep via new addition. As previously stated, such quantities go-to substitute old stock and add new possibilities. Altogether, with the recovery sector, productivity and income have overall increases. Our problem is therefore declined in such manner:

$$\max_{C,N,F} W = \int U(C_t, N_t) e^{-\rho t} dt \tag{30}$$

$$H_t = U_t e^{-\rho t} + \lambda_t (Y_t - C_t - F_t - pN_t - \delta K_t) + \mu_t \eta F_t + \nu_t (N_t - dM_t)$$

The Hamiltonian H comprises the actualized utility function and each differential equation multiplied by the proper shadow prices. The first step to solve the problem is to derive control equations:

$$\frac{\partial H_t}{\partial C_t} = 0 \rightarrow C_t = \frac{1}{\lambda_t e^{\rho t}} \tag{31}$$

$$\frac{\partial H_t}{\partial N_t} = 0 \rightarrow p\lambda_t = \nu_t$$

$$\frac{\partial H_t}{\partial F_t} = 0 \rightarrow \lambda_t = \eta\mu_t$$

The consumption equation is consistent with Ramsey–Cass–Koopmans model one. We tested the stability of the system similarly. Proportionality of capital and technological stock shadow prices offers some simplifications. Using conditions from equations 31.2 and 31.3, we can see that F is equal to capital change. As for production, we can see that the problem has two main differential equations: capital and material stock. We presented the mathematical passages within the appendix.

$$\frac{\partial H_t}{\partial K_t} = \rho\lambda_t - \dot{\lambda}_t \rightarrow \lambda_t = \lambda_0 e^{(\rho - Y_K + \delta)t} \tag{32}$$

$$\frac{\partial H_t}{\partial B_t} \rightarrow U_B e^{-\rho t} + \eta\mu_t Y_B = \rho\mu_t - \dot{\mu}_t \tag{33}$$

$$\frac{\partial H_t}{\partial M_t} \rightarrow \rho\nu_t - \dot{\nu}_t = \nu_t\left(\frac{1}{p}Y_M - d\right) + U_M e^{-\rho t} \tag{34}$$

$$U_C = \lambda_t e^{\rho t} \tag{35}$$

The accumulation of commodities and satisfaction of other necessities reflects inter-temporal decisions. We call elasticity of intertemporal substitution the responsiveness of consumption to the production factor returns. If we look at consumption, its responsiveness reflects the market return of capital. The responsiveness of net addition reflects market return from material stock M minus generic capital return. It is possible to see that the stock of material flow and technology is necessarily proportional in the long-term, using the implication of linear interaction of shadow prices. This allows for a strong reduction in the system's complexity, reducing the model to two variables.

$$\frac{\dot{C}_t}{C_t} = \frac{1}{\sigma_C}(Y_K - \delta - 2\rho) \tag{36}$$

$$\dot{K} = \frac{1}{3+d}(Y - C - \delta K) \tag{37}$$

The solutions to the model should not differ drastically from the Solow-Swan outcome. The main particularity is a discounting factor weights the market interest rate for spent materials. For our study, it is worth mentioning that capital and production are drivers of material accumulation's long-term stability.

$$M = \frac{1}{dp} - \frac{e^{-d(K-K_0)}}{d} \tag{38}$$

The steady-state is therefore inversely proportional to the spent factor "d" and price "p" in equation (38). The positive relationship with capital is matched by technological stock B, according to the efficiency "η". We presented this relation in equation (39)

$$M = \frac{1}{dp} - \frac{e^{-\frac{d}{\eta}(B-B_0)}}{d} \quad (39)$$

The modeling has outlined two operative hypotheses to estimate drivers of accumulation. The first one relates the decoupling dynamics between economic growth and material accumulation. While the economic cycle evolves according to a Ramsey–Cass–Koopmans model, material accumulation and technological change are partly redundant if the expenses to maintain them are linear. In this sense, is the interest rates contemplates the weight of spent commodities, theory of circularity works exactly are most theoretical premises of green growth. Therefore, an Environmental Kuznets Curve (EKC) setting will be outlined within the statistical model to test for tipping points in economic activity against material accumulation. Secondly, investments in a Circular Economy are difficult to trace, by the stock of patents is a close representation of the variable B. Therefore, innovation stock could affect material accumulation too.

While this dynamic optimization presented the theoretical premise of generic material accumulation, it cannot explain the alone distribution of commodities within the stock. Instead of estimating another model with several commodities, we derived an equation from the equation (28.1).

Stock Complexity

Composition varies linearly with innovation/design and non-linearly with the economic cycle. This will be the hypothesis tested with statistical models. The current approach to functional test form around matter vs. economy is the environmental Kuznets curve. Considering that we assume, parameters “a” and “b” to be unique for each material, heterogeneity might arise among results. Hence, the composition of EEE may resemble decoupling for some and no relation with others. Circular Economy innovation indirectly affects the design of commodities. The economic cycle uses the budget to add new commodities and replace old ones to be recycled. Therefore, a rational planner will calibrate the stock composition to maximize its secondary material output. The relation between innovation stock and material stock should be then positive, indicating a positive value of circular productivityϵ_t. Indeed, this stock is a driver of material accumulation. Another aspect we can test is the relation between per-capita stock and stock complexity. Since it is difficult to understand the dynamics of functionalities brought by each new stock Kg of EEE, it is possible to assume that composition and weight have some form of interaction. The cycle could be addressed in terms of information theory and complexity. In theory, the maximum level of chaos stands between the minimum and the maximum probabilities of a set. In our case, we do not talk of statistical variabilities but proportions within a basket of commodities. All identical commodities or perfect distribution of proportions represent the lowest levels of complexity. Complexity stands in the middle of these two possibilities. The relevance of the last variable can be intuitively described as such. EEE resembles a diverse set of commodities with different composition matrixes. In case one commodity is predominant in weight, its materials will be defined in total EEE composition. Departing from the definition of stock variation, we can rewrite it as in equation 40.

$$\sum_{\forall n}\frac{\dot{M}_{nt}}{M_{nt}}=\sum_{\forall n}\frac{N_{nt}}{M_{nt}}-\sum_{\forall n}d_{nt} \tag{40}$$

From this identity, we continue with two passages. The first one is a simple transposition of the previous, keeping the signs:

$$\sum_{\forall n}\frac{\dot{M}_{nt}}{M_{nt}}-\sum_{\forall n}\frac{N_{nt}}{M_{nt}}=-\sum_{\forall n}d_{nt} \tag{41}$$

The second one applies the natural logarithm to both terms, as in equation 42.

$$\sum_{\forall n}ln\left(\frac{\dot{M}_{nt}}{M_{nt}}\right)=\sum_{\forall n}\frac{1}{ln(d_{nt})}\sum_{\forall n}ln\left(\frac{N_{nt}}{M_{nt}}\right) \tag{42}$$

By multiplying both terms of the last equation by the former one, we have:

$$-\sum_{\forall n}d_{nt}\,ln(d_{nt})\sum_{\forall n}ln\left(\frac{\dot{M}_{nt}}{M_{nt}}\right)=\left(\sum_{\forall n}\frac{\dot{M}_{nt}}{M_{nt}}-\sum_{\forall n}\frac{N_{nt}}{M_{nt}}\right)\sum_{\forall n}ln\left(\frac{N_{nt}}{M_{nt}}\right) \tag{43}$$

We can spot the entropy equations of durability (Sd) and entropy of relative acquisitions (SN) in both terms. The definition of entropy does not stem from the typical literature in environmental and ecological economics. We are referring to the information entropy used in information theory (Shannon, 1948). By revising the equation with these definitions, we see that entropy of relative new addition is logistically related to stock growth:

$$S_n=\left(S_d-\sum_{\forall n}d_n\frac{\dot{M}_{nt}}{M_{nt}}\right)\sum_{\forall n}ln\left(\frac{\dot{M}_{nt}}{M_{nt}}\right) \tag{44}$$

The definition of entropy we used represents the concentrations of concentration. The higher its value, the less concentrated is the composition of commodities of EEE stock. Stock growth is generally higher between the start point and the steady states. Low entropy, hence high concentration, affects, as previously stated, the material composition of total stock. Therefore, stock maturity that is determined by the economic cycle affects new addition concentration and then material composition. The cycle could resemble as follows. The first steps of accumulation are driven by novelty; thus, the set is increasingly complex. Once the novelty passes, each new addition covers discovered functionalities. After this tipping point, complexity reduces. Linking this analogy with the previous hypothesis, we need to prove that material distribution is a predictor of material composition, altogether with the economic cycle and material stock.

To sum up the theoretical premise, the economic system should select material composition according to the Anthroposphere's endogenous variables. A society decides according to its income the number of net additions N, determining which should be the composition "c", therefore "S". Net additions cumulate until reaching a steady state. Since income affects necessarily stock and "S", we need to test models separately to avoid endogeneity bias. Furthermore, aggregated timespan could be effective in determining the distribution of commodities. It will be considered too.

The econometric model

The theoretical premise has some weak aspects that need to be tested. For instance, the closed economy hypothesis would mean that cross-sectional dependence is null or negligible in panel data. This should be untrue in our dataset, as we expect that within the EU panel, strong cross-sectional reliance occurred. The estimation will require a strategy to counter such methodological limitations. The feasible generalized least squares (FGLS) trades sensitivity with robustness to biases in our theoretical model. In case estimated models respond with significance, the strategy will repay the cost of sensitivity loss. This aspect is relevant due to the clustering of the European Union. As we are going to see in the next section, economic differences among nations induce high heterogeneity. Two approaches were used. One is clustering, and variable choices represent the other. We added socio-economic factors to capture specific differences among nations. Physical variables are added to differentiate the intrinsic differences of EEE stock within clusters. We used patents for innovation stock.

$$Y = X\beta + \gamma p + \theta age + \varepsilon \tag{44}$$

The impact of patent use in material-economy nexus has been studied before (Bringezu et al., 2004; Steger & Bleischwitz, 2011). We will apply the EKC hypothesis to GDP since we expect nonlinearities and decoupling dynamics due to literature results and theoretical models. This will allow searching for tipping points. Since we expect similar dynamics with the composition, we will apply a similar formula to the Shannon index. We explained the statistical model in equation (44). Variable X refers to either GDP per capita as EKC (model 1), Shannon index as EKC (model 2), or Stock per capita (model 3). Variable p represents the cumulated sum of patents as a knowledge stock for circular applications. We used these variables to control for "innovation" within this sector. As a socio-economic variable, we used the percentage of the population over the age of 65. As elders tend to consume and replace less EEE, this information is relevant, not using computers or IoT.

Data

Our work uses a collection of socio-physical data. Material variables comprise Stock per capita, Shannon index, and average timespan. They refer to the material component of our modeling. We took these data from the results of the ProSum project. The original dataset classifies the stock variation of EEE and its commodity components. Variation of the stock is defined as the sum of all net addition minus the discarded ones. The new addition is referred to with ProdCom digits codes. Since the study of product lifespan has been made in UNU-key, all new additions are then aggregated according to the latter key. Time-span is then applied Shannon index is derived as explained in the previous section from each product that defines the EEE in-use stock. Timespan is assumed to be constant per product category. To aggregate the overall stock value, we used a weighted mean according to pieces of each category. Classification according to Strata follows the same division of the last chapter, where the first is considered the richest countries of Europe and the third the last applicants to EU union. Since we witness this variability across income groups, we will apply the statistical model to the total sample and then repeat

	Stock pro Capita	Shannon index	Average Time-span	GDP pro capita	Population Ratio over 65	Cumulated Patents	WEEEP	WFD
Stock pro Capita	1	0.755	0.226	0.814	0.286	0.316	0.277	0.384
Shannon index	0.755	1	0.153	0.684	0.09	0.143	0.045	0.217
Average Timespan	0.226	0.153	1	0.024	0.096	0.091	0.128	0.098
GDP pro capita	0.814	0.684	0.024	1	0.019	0.15	0.135	0.255
Population Ratio over 65	0.286	0.09	0.096	0.019	1	0.267	0.349	0.357
Cumulated Patents	0.316	0.143	0.091	0.15	0.267	1	0.04	0.042
WEEEP	0.277	0.045	0.128	0.135	0.349	0.04	1	0.577
WFD	0.384	0.217	0.098	0.255	0.357	0.042	0.577	1

Table 9: Correlation table

it for the three Strata. We collected Gross Domestic Product (GDP) per capita, population ratio over 65 years of age, and socio-economic variables. Since this class of individuals tends, on average, to be less connected to IoT and recent addition to technology (Peacock & Künemund, 2007), we assumed there could be some effect on EEE stock accumulation or composition. To measure the impact of recycling innovation, we created a "patent stock" variable to capture the effect that "B" might have on accumulation. We used the dataset from Eurostat for patents involved in Circular Economy and waste recycling. It is, therefore, a sectorial innovation stock. We chose it as a proxy for the technological evolution of the circular sector. Its regressor will measure the impact that technological growth has on stock accumulation and composition. Finally, we added the two main policies that affected the global EU in terms of waste collection, Waste framework package classification (WFP) and the WEEE package (WEEEP). They are dummy variables with 1 when they are implemented and 0 as the time before. We expect them to capture the structural changes that affected EEE accumulation in recent twenty years. Since these two variables are strictly time effects, we will not employ time dummies for our regressions.

The correlation matrix is presented in table 9. Socio-economic variables have a strong correlation with physical variables, as expected. Dummy variables are strongly correlated with population ratio, GDP per capita, and patent stock. To assess the endogeneity impact, we will use the correlation between residual and dependent values as a rule of thumb. Since we need to estimate the relation that policies have to keep constant socio-economic variables, we will focus on the other endogeneity issue. Patent stock is, for instance, correlated to the population age ratio. This is interesting as we were expecting significant effects, given the relationship that investments and the economic cycle have. It is more probable to find cumulated patents in nations with a higher quota of the elderly population.

I reported the summary of the variable in table 10. Material variables are leptokurtic, with narrower distributions concerning socio-economic variables. Among the three, the material stock is the most complex. The start value for the most nation was around 80 Kg per capita, while in the end reached almost 300 Kg. The composition changed too. We multiplied the Shannon index to 1000 to scope the variation better. It has a distribution with a low standard deviation. Time-span, as previously noted, changed greatly between Strata.

Variable	Observations	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Stock pro capite	448	186.306	61.463	49.509	140.694	236.817	308.45
Shannon index*1000	448	3121	15.7	2433	3038	3244	3369
Average Timespan	448	22.861	1.179	19.668	22.164	23.606	26.206
GDP pro capite	448	28288.37	20429.75	1613.867	13213.87	41561.37	120188.8
Population ratio over 65	448	0.161	0.023	0.108	0.144	0.177	0.217
Cumulated Patents	448	11.004	21.151	0	0.59	12.283	141.66
WEEEP	448	0.25	0.433	0	0	0.2	1
WFD	448	0.5	0.501	0	0	1	1

Table 10: Summary Statistics

This definition reflects the distinction of economic activity within EU27+UK. The division is into three main groups. Nations above 35.784 Euros are considered first Stratum (Austria, Netherland, Ireland, Sweden, Belgium, Denmark, Germany, United Kingdom, Finland, France, and Luxemburg). Within the second, it is possible to find nations with a GDP per capita Between 23.068 and 30.289 Euros (Spain, Slovenia, Cyprus, Czech Republic, Malta, Portugal, Slovakia, Italy, and Greece). Finally, below 23.068 Euros lay nations of the third Stratum (Poland, Hungary, Estonia, Croatia, Lithuania, Latvia, Bulgaria, and Romania). In terms of lifespan, the weighted mean of the stock is 22 years. Composition in commodities changed its value between a minimum of 19.7 years rounded to 26 rounded. As it is possible to see in Figure18, this is a variable changing according to Stratum and time. It is probably due to the variation in composition and preponderance of certain categories of EEE. For instance, heavy domestic appliances have a longer timespan than light ones. It is possible that in case of a reduction in average timespan, the economy is relatively accumulating lighter household appliances such as computers. GDP variability is widely noted and is clearly defined by the division expressed before. In fifteen years, it is possible to find Europeans with a GDP per capita of 1600 (Bulgaria 2000) to more than 120000 (Luxemburg 2015). Similar heterogeneity affects patent accumulation, as the maximum 141 is more than ten times the mean (11).

Overall, socio-economic heterogeneity requires clustering the application of the model. It is possible that each *Stratum* accumulated EEE differently during the period. Due to high correlation, we strategically chose to estimate models to avoid cross-selection issues. We decide to split the result into three cases, one for each class. Nevertheless, we will present the first result according to EU27+UK in table 11.

Results

Across Eu27+UK, socio-economic variable largely explains both material variables under the scope. Both policies seem to be effective in affecting the composition and material accumulation. WEEEP has negatively affected composition, while WFD increased it. A possible explanation might be related to the objectives and timing of policies. According to chronological order, the former was approved two years before the economic crash and the same year of Leman' Brothers' failure. Therefore, demand still had to adjust to the crisis. Or, more importantly, since it is linearly correlated to stock, the first break may be registered before the peak. In general, the policy itself has imposed standards, and waste reduction targets valid across Europe, determining a break in terms of waste policy overall. We find specific changes with the second policy. It refers to the waste categories of waste, practices, and producer responsibility. This might have affected collection and, therefore, stock dynamics. We suggest interpreting results jointly.

To summarize, waste policies are correlated across Europe with a reduction in EEE stock complexity and reduction increase in stock weight per capita. This outcome acquires general relevance when read with an average timespan. Considering it is effective only on composition but not for total weight, new additions may have been neutral to the latter. Stock is a proxy for functionalities and the physical mass that embed them. In case the stock is constant, and shares change, EU citizens acquired new functionalities keeping stable in-use mass. The role of European policies has determined *ceteris paribus* an increase in terms of importance. This means that it slowed down the effect of substitution. Again, the timespan effect is not statistically significant in all cases. In general, our hypothesis of the material-technology cycle is not valid as patents and timespan are not substantial for all *Strata* together. In-use stock registers a tipping point with the Shannon index. Furthermore, we register a possible decoupling mechanism for GDP and stock as in EKC. We will use this model as a yardstick to compare the *Strata* for their cycles.

Stratum 1

European countries with GDP per capita higher than 30000 euros register strong economic cycle significance and material cycle. For instance, time durability affects the distribution of commodities within the stock and the stock mass. The former negatively, while the latter positively, probably due to the longer timespan that only certain commodities have. Therefore, the increased average commodity timespan is related to the increased importance of heavy equipment within First Stratum countries. Technological innovation in circularity positively affects material accumulation and negative composition.

Interestingly, WFD has did not affect the composition, keeping the same effect on the stock as the whole panel EU27+UK. It probably means that it did not produce a positive effect on total functionalities for the rest of Europe. UKC supports both material settings and the socio-economic cycle. This means that material stock in rich countries has decoupled economic growth. Secondly, increases in mass have reached the saturation of functionalities. The elderly population negatively affects composition. To summarize, material variables fit similarly to the socio-economic cycle. Stock complexity is saturated, and the economic cycle decouples by material accumulation. Policies and technological stock positively affect material accumulation.

Stratum 2

This stratum defines a broad category of nations in the EU. It is the middle-tier category of income. In this case, we find a weak presence of the material-technological cycle. For instance, circular patents stock has positively affected the EEE per pro capita, but not its composition. Timespan again does not affect it; however, it is strongly correlated with mass. Waste policies have jointly had a more conservative effect on mass/composition dynamics. Since policies have been less effective on composition but are generally effective on total weight, this stratum may still be in a transition phase. In this sense, the socio-economic cycle seemingly affects the previous models' material cycle, but it is not the only factor. Intrinsic variables are less fitting, and technological and policy variables too. Economic cycle and technological stock present similar estimates as the previous; despite the weight of the elderly population, such as in Italy, this variable is insignificant in determining the composition of EEE stock.

Stratum 3

The last result presents the outcome from the estimation of our models for the third *Stratum*. Concerning the other models, material cycle models are relatively more fitting than the previous one. Cycles work similarly, but policies have been somewhat less significant in affecting composition. Timespan, cumulative patents, and elderly population do not affect the composition, but rather on weight. Policies under consideration have had a significant and great effect, as much in the first *Stratum*.

Interestingly, GDP has similar effects here as in previous models. Despite this continuity in results, the condition of less fitting is curious. We conclude that the economic cycle is still immature to determine other variables.

According to our results, the hypothesis underlined by the theoretical model is overall correct. The distinction in control variables such as population dynamics and intrinsic variables is dependent on the Stratum. It is not surprising as stark differences in EEE stock characterize these three groups. Economies accumulate EEE commodities according to their needs, with weight and composition dynamics as strongly correlated. As they grow, both economic and material cycle concur for function accumulation. As decoupling incised, the economic cycle mainly defines functionality accumulations rather than gross weight. According to our preliminary results, waste policies have significantly affected the distribution's tails and have had a lesser effect on middle-tier economies. Results do not underpin overall the technological feedback from circularity patents.

Discussion

In this section, we will elaborate on the results to supply a proper narrative. The novelty of using material stock complexity underlines interesting points to material policy. Since consumers acquire a different set of commodities, they indirectly choose their material too. Performances and materials are embedded within the commodity. Thus, the market receives feedback on how to design commodities. Thus, it is probable that policies that aim to benefit consumers' choices have an indirect effect on commodities' material composition.

The policies considered are two. The first is the WEEEP. They are approved for the creation of collection schemes where consumers return their WEEE free of charge. This directive aims to increase the recycling of WEEE and/or re-use[21]. The other policy is the WFD. The determination of a hierarchy was the policy breakthrough in waste management and prevention. The objective was to reduce as much as possible the volumes of waste produced. According to our results, both policies have induced increases in accumulated EEE. One possible explanation was that consumers started to reduce waste, therefore retaining some of the commodities. Since waste was reduced and net addition was seemingly constant over time, consumers kept accumulating. This is a positive outcome for secondary materials. Considering the rarity of CRM in the EU, EEE represents a viable mine within our economies. Anthropospheric mining represents a useful resource for other stock, such as automotive and airborne sectors.

[21] https://ec.europa.eu/environment/waste/weee/index_en.htm#:~:text=The%20new%20WEEE%20Directive%202012,into%20force%20in%20February%202003

Table 11: Results from the model estimation

	Stratum											
	EU27+UK			1			2			3		
	Shannon Index		Stock	Shannon Index		Stock	Shannon Index		Stock	Shannon Index		Stock
Stock pro capita	4.839***			4.257***			4.959***			5.357***		
	(0.440)			(0.705)			(0.766)			(0.805)		
Stock pro capite^2	-0.007***			-0.006***			-0.007***			-0.009***		
	(0.001)			(0.002)			(0.002)			(0.002)		
Average Timespan	-6.877*	4.939	4.000***	-14.316**	-2.602	5.043***	0.753	9.067	2.293*	-7.537	6.956	4.050**
	(4.004)	(3.823)	(0.802)	(6.364)	(6.022)	(1.269)	(7.201)	(6.840)	(1.344)	(7.232)	(7.128)	(1.611)
Population ratio over 65	-603.245***			-710.505**			-327.327			-737.736*		
	(216.442)			(340.935)			(393.089)			(389.226)		
Cumulative Patents	-0.626***	-0.559***	0.249***	-0.663*	-0.767**	0.230***	-0.444	-0.213	0.236***	-0.743	-0.597	0.291***
	(0.228)	(0.214)	(0.045)	(0.355)	(0.322)	(0.068)	(0.390)	(0.364)	(0.071)	(0.456)	(0.449)	(0.102)
WFD 2008	5.599	18.866*	11.068***	-8.899	2.830	11.795***	20.964	32.453*	8.336**	6.690	25.214	13.112***
	(11.503)	(10.872)	(2.282)	(18.020)	(16.783)	(3.537)	(20.882)	(19.529)	(3.838)	(20.609)	(20.323)	(4.593)
WEEEP 2012	-55.484***	-37.664***	12.851***	-53.960***	-39.800**	10.483***	-62.862***	-30.311	17.865***	-51.059**	-42.779*	11.822**
	(12.820)	(12.259)	(2.573)	(20.058)	(18.941)	(3.992)	(23.199)	(22.245)	(4.372)	(23.267)	(22.599)	(5.107)
GDP pro capita		0.013***	0.005***		0.013***	0.005***		0.014***	0.005***		0.013***	0.005***
		(0.001)	(0.000)		(0.001)	(0.000)		(0.001)	(0.000)		(0.001)	(0.000)
GDP pro capite^2		-0.000***	-0.000***		-0.000***	-0.000***		-0.000***	-0.000***		-0.000***	-0.000***
		(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)
Constant	2,771.404***	2,750.043***	-21.511	3,022.746***	2,937.656***	-46.170	2,529.089***	2,628.996***	14.730	2,763.938***	2,714.305***	-20.214
	(92.035)	(85.787)	(18.006)	(150.576)	(136.705)	(28.810)	(164.147)	(151.519)	(29.781)	(162.029)	(159.640)	(36.078)
Observations	448	448	448	176	176	176	144	144	144	128	128	128
Countries	28	28	28	11	11	11	9	9	9	8	8	8
R^2	0.491	0.490	0.893	0.441	0.464	0.902	0.606	0.579	0.913	0.522	0.503	0.888

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

For policymaking purposes, it is relevant to point out that our model does not distinguish between the market value of secondary materials of EEE and their recovered units. In other words, we assumed that the social planner somehow managed to control the cost of recovery within production cost. Another aspect is that the system tends to reduce the amount of irrecoverable mass (1-a). It is consistent with the policy implementation of WEEEP and WFD. The implementation of waste hierarchy defined the most undesirable flows. Such practice has reduced the production of total waste, probably affecting total accumulation. Nations and firms abided accordingly, redesigning products and collecting plans. Similarly, WEEEP ordered a framework for the collection cost-free for the consumer. Such practice has internalized the cost of collection within the prices. Therefore, policy dummies are controlled for such aspects.

This chapter linked the economic cycle with stock dynamics and stock composition/complexity. According to our result, the composition indicator is explained by the stock accumulation according to an inverted “U” functional form: after a tipping point total weight of EEE decouples stock complexity. We can express such relation in three main phases. At a start point, the economic cycle is still at an immature stage; therefore, net addition is neither complex nor heavy. After the accumulation of financial capital and innovation, the economy grows faster. We most probably find the peak in complexity due to the value that new functionalities have in this stage. Managing complex information is one of the main drivers of welfare during the post-industrial stage. The cost of new additions is linear, but its returns are logistic. Therefore, it is more difficult to increase the dimension of stock weight and complexity at the frontier. The former of the two is probably affected by the preference in terms of functionalities. Lighter and better-performing commodities probably have higher material complexity requirements; indeed, total weight is expected to be lower. Therefore, it is challenging to increase total manufactured stock weight at this stage in absolute dimensions. Most new additions are necessarily smaller and more complex. This is the main driver of new additions until substitution appears. Net addition tends to be zero. Hence, the complexity of net addition should be lower at the mature stage of the economic cycle. These results are relevant for environmental economics in two main ways. If it is possible to predict medium- and long-term new EEE material stock additions, we can set material recycling objectives based on real necessities.

Knowledge of recycling affects how much an economy dependent on foreign extraction and commodities production. Despite the best effort, these activities are environmentally intensive (especially the former) and socio-economically intensive (both). However, our study helps comprehend that if we consider the recycling sector as a source of raw materials or new commodities, circularity can partly reduce the dependency on external or virgin sources. The recycling sector has two main limits: how much commodities are wasted and how effective recycling technology is. Many authors call it the entropy problem. Secondly, if this model consistently predicts the economic cycle and material cycle, we should expect higher pressure on mining-related to EEE in next years. Nations entering the stage of development will require more material stock. This will add new functionalities and affect welfare, culture, and democratization. Therefore, the economic cycle might require higher environmental pressure in future years. In terms of priorities, two main approaches of sustainability might assist. We could call one the nexus of strong sustainability and lower information. It refers to the influence that precautionary principle should limit as much as possible mining activity and manufacturing outside circularity. This approach might induce de-growth, reducing the number of functionalities. This would affect information. We think this vision might under-estimate the role that information and knowledge have in solving problems. The other is the weak sustainability with high information. In this setting, policymaking aims to increase access to food, knowledge, and information access globally. The cost might be the increased environmental pressure. The relaxation of the precautionary principle is derived by the higher weight this vision gives to technology, knowledge, and general information. We believe that no matter the perspective, the EEE issue relates to both visions.

Conclusion

In this chapter, an effort is made to define the theoretical dynamics between accumulation, economic cycle, and technological growth. We departed from a vanilla growth model using resource stock that increases over time. This economy reuses part of the waste produced for production. Material recovery from commodities could be assimilated to mining for social ecology. To model flows of matter, data from inflow-driven methodologies is recalled. The social planner improves welfare by increasing consumption and the new addition of material stock. This is employed as a factor of production jointly with capital and recycled waste. The investment cycle drives research, new addition acquisition, and capital accumulation. Research investments are cumulated in a stock affecting the recycling rate until its limit. Since waste is proportional to material stock, we simplified the production function as having two input variables. Productivity is therefore positively affected by each investment. The cost of recycling is null budget. The conclusion to the model was several. Material accumulation and complexity have a tipping point as EKC hypothesis, and innovation stock affects material accumulation, and the socio-economic cycle decouples material accumulation. In this study, we linked them by giving a theoretical explanation and an applied model. We used as example EEE: they contain a wide variety of materials, a general concern for its waste, and their acquisition signal the access to welfare. Our analysis shows that the EEE category's complexity, economic growth, and material stock are highly correlated. We believe such a phenomenon is related to material stock maturity. For endogenous growth, the material stock tends to evolve and become more complex, heavier, and evolve according to economic growth. As the nexus reaches a steady-state, complexity reduces, converging to a constant value due to the heterogeneous life cycle of commodities. Overall, the nexus considers two main tipping points from statistical results. One is the complexity, and the other is the weight per capita. Accumulation of EEE positively affects complexity until an estimated tipping point, indicated by the estimates' inverted signs. We interpreted this as the maturity of the stock in terms of acquired functionalities. As the stock reaches maximum complexity, there is no new product to accumulate. Without novelty, the accumulation represents just new weight.

Similarly, with mass per capita, the economic cycle satisfies the EKC due to the different estimates. Despite the intention to address differences between the Strata's various economic growth levels, estimated cycles are overall similar. This means that the estimated maturity for the nexus exists *ceteris paribus*. Controls varied without affecting the results of our main hypothesis. Our theoretical model was statistically consistent. Policy dummies proved to be compatible for waste effect but not overall significant for material complexity. We interpreted such a result as a retention from consumers.

The chapter offers a unique insight into the material stock-economic cycle nexus. In environmental economics, a theory of production and material recovery is defined. The dynamic between material complexity and stock growth is studied in model and estimation, presenting interesting stock saturation studies. Finally, the relation between the average product timespan and other EEE variables is presented. The application over the EEE allowed us to take a look into the intersection with complexity and in-use mass. Complexity was intended to be a proxy of the functionality set that the EU resident could acquire. The difference with cited literature stands in the analysis object too. Most studies preferred to focus on "static" stock.

Cited literature focused on material use, a sum of gravel raw materials. Inflow-driven works are strongly interested in the infrastructure dimension. Our insight into the complexity is less relevant to the monolithic aspects of static material stock. A variety of functionalities composes sectors such as automotive and airborne services. This work could represent a valid starting point to evaluate the maturity dynamics of those mobile stocks. We need to consider such aspects for various set of reasons. They embed CRM such as REE and other Green materials, strategic for the carbon transition (Church & Crawford, 2020). Furthermore, addressing secondary material potential and anthropogenic mining could temperate the risk of the stranded assets in case of hard transition (Busch et al., 2014; Campiglio et al., 2018; Thomä & Chenet, 2017). Proper assessment of material flows and their recycling potential could present a relevant element for the Circular Economy. From its pure material point, it has positive benefits for climate change. Mobile and immobile stocks could be reconverted using material recovery by an advanced recycling sector. Outside dynamics of the long-term, management of secondary materials has major benefits for market security. Some of the CRMs are located in few key exporters, such as the Popular Republic of China, the Democratic Republic of Congo, and Russia (ERECON, 2014). Our material stock is approaching the state of maturity; hence every addition is mainly substituting old equipment. Circular management could hinder the dependency from external and sometimes volatile exporters.

Thesis Conclusions

The thesis has presented several topics regarding material circularity. We highlighted the vicinity and potential applications of a nexus political/social Ecology and environmental economics within the literature section. Instead of natural ones, the definition of artificial reservoirs has the theoretical potential to reduce the Geosphere's human colonization's negative effects. Furthermore, the neoclassical framework of environmental economics can elaborate and test politically acceptable solutions. For instance, many scholars have defended de-growth policies to achieve the transition to a more sustainable society. I believe it is not needed an extensive literature review of financial studies or public policy to find the practitioners' repulsion for such option, or at least considering them only as a last resort. For instance, if Critical Raw Materials-related products generate negative outcomes from waste treatment, an exclusion-based (de-growth friendly) regulation could be preferable. The European Union's response focused on circular innovation, responsible sourcing, and recycling, still a growth-friendly approach.

According to our study, the international supply chain can adapt to stringent Due Diligence requirements. China's main competition could represent more of a short-term source of the problem than a long-term one. Reducing total waste is the best option for circular transition. Recovery from spent products represents a valid second best, with great potential for securing the long-term-supply of critical raw materials. Circular innovation seems to foster both objectives, allowing, in the end, greater material retention and accumulation. Furthermore, waste policies have accelerated such a process, even considering the diverse economic development level of EU nations. Therefore, circular policies proved to have an indirect effect on material accumulation (EEE in particular).

From this work, five main articles could be produced. The research lines are mainly two. One refers to the mineral governance regarding the external efforts. Following the first chapter's position, we find a critical analysis for CRM regarding human rights vulnerability and circularity. Our findings underlined the trade-off that green materials create between the potential recovery and market security. Transition to a low-carbon society requires such a collection of materials under the form of complex manufactured goods. Their production is entangled with local conflicts and violations of human rights. In terms of maximum vulnerability, EV represents the most endangered commodity of a green transition.

The second line was the management of the artificial reservoir. Waste management could be interpreted as colonization of in-use material stock. The outcomes of the research could be resumed in reproducible research and datasets. The dataset employed in the third chapter has been applied in two other research works for MSW at the provincial level. The study found significant nonlinearity within the relation between economic activity and MSW. The complexity could be resumed in spatial heterogeneity. The model could be reused for particularistic analysis at a very low level of scaling, political cycles, and temporal breaks studies. The application of vulnerability was a novelty to the field, and its variability might redefine how we evaluate tipping points with policies. The Italian dataset has allowed for the study of the economic impact of WEEE generation. As reported by the fourth chapter, this flow is a repository of precious elements strategic for the European mineral governance. According to the study I made, the reserve/resource of CRM is determined by innovation, economic cycle, and diversity in EEE in-use stock. In synthesis, richer countries have easier access to precious elements due to intrinsic differences of in-use stock considering equal technological use. Furthermore, the thesis focused on EEE, but rich basins could be found in the automotive, civilian air, and naval sectors. The scale of results would be greatly larger.

While the efforts of this thesis produced novelties for academic literature, we found several gaps. Following the thesis structure, we found few studies relating to Due Diligence's effects on international trade. Operational variables identifying the institutional quality are still at the national level and consist mainly of ratings. This reduces the comparability among violations and improvements of the supply chain. Therefore, increased disclosure will be effective only if academics engage the field and start producing indicators of Due Diligence capable of assessing the transition at the micro (firm levels, such as ESG) and macro-level (such as human development index and institutional quality indicators). In terms of material flow studies, mainly two materials were recently studied, Cobalt and Lithium. However, the list of critical raw materials increases and commodities composition continues to vary. The capability to predict how the composition will evolve could impact studies that assess artificial reservoirs. In the last chapter, the hypothesis presumed that innovation has a measurable and predictable impact on accumulation outside recycling. The possibility of allowing uncertainty in innovation results could impact how we design circular policies in the long-term. Using stochastic modeling terminology, the drift factor of technology (the variance of expected results) could seriously affect investment decisions, excessively favoring precautionary strategies. Still, this is not a common feature of mainstream growth models.

The data elaborated for this thesis could in part respond to the gap highlighted here. The socio/economic dynamic of Italian panel data has been updated with management data from costs and types of treatment from 2015 to 2018. It might allow for insights into policy choices and cost analysis. For instance, few studies motivate the heterogeneity in performances according to the cost-effectiveness function. Studies on the political cycles within the provincial cycles are have never been appropriately addressed, while they could partially motivate the divergence. In terms of material Due diligence, the EJAtlas scraping process allowed extrapolating geo-localized data on violations matched with responsible corporations.

Overall, we have seen that a strict division of pessimism/optimism does not fit Environmental policies. While neo-Malthusian approaches will always be inherently pessimistic, environmental economists will tend to optimistic modeling. Our study involved both visions in dealing with Mineral Governance. Circular Economy does not have all the answers for the transition to a sustainable Post-Industrial Society. However, it fosters a reduction in waste, dependency on imports and mining, and positively impacts common welfare. Our studies suggested that improvements in circularity targets will increase the per-capita in-use stock of Electrical and Electronic Equipment; besides, new commodities will be produced in safe conditions to foster human rights. Circular Economy's socio-economic values are related to the capacity to control, stock, and sustainably transform artificial reservoirs. In the post-industrial society, complex commodities related to digitalization are crucial to elaborate complex information in a short time. However, these potentials have to abide by the flaws and limits that this thesis has explored. We can improve the understanding of the limits and potentials of Circular Economy, along with its political and material influence in the transition we are currently experiencing.

Appendix

Material cycle in MSW and data

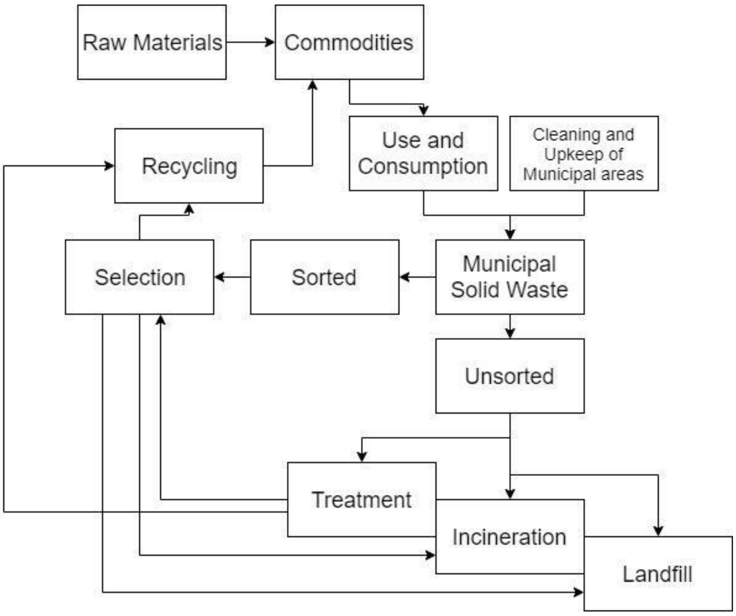

Figure 18: Material Flow Chart

Cited literature tends to apply various MSW definitions without a debug of its composition or direction in a material chain. It represents the sum of sorted and unsorted flows. These are defined after collection from bins, door to door, and other policies. At this point, both can either be incinerated, landfilled, or processed for recycling. ISPRA does not identify the form of incineration at this point. Furthermore, the amount of recycling is unclear. Clothes are usually reused for secondary sales or donations after the sanitary procedures. Other flows might be recycled in the sense of material recovery. Therefore, WEEE might be treated to extract precious materials and so on. Confusion of these two terms is evident in this case, and caution is needed when applying such data. In our case, we mainly focused on the total collection and sorted ones. We left out the unsorted one.

Tipping points and possible functional Forms

This section briefly presents how the first and second moment to change according to each parameter change. We refer to the equation for a family of FF where the first polynomial is used. It takes such form:

$$y = ax + bx^c$$

Results are reported in Table 4 as a theoretical examination. It must be noted that complexity arises as each parameter is presented. Tipping points “x” in FF is strictly positive on “a”. This is trivial as it represents the interaction between a linear independent variable and a dependent one. Hence, we have positive signs of both moments of “x” for “a”. Parameter “b” is convex to its tipping point. This is where we can find two different FF: either U or its inverted shape. Its signs are different. The last parameter we considered is “c”. Here, the number of functional forms is the maximum reported in the literature.

Nonlinearity is evident as the value of "c" is influencing the sign of the first moment. X's tipping point is strictly linear to "c" when its values are less than one. In other cases, it is concave, denoting other nonlinearities. We cannot find examples in the literature where "c" has values different than 2.

Table 12: First and second moments of the tipping point

	First derivative	Second derivative
a	$\hat{x}_a = \hat{x}\frac{1}{a(c-1)} > 0$	$\hat{x}_{aa} = -(c-2)\hat{x}\frac{1}{a^2(c-1)^2}$ $c < 2, \hat{x}_{aa} < 0$ $c \geq 2, \quad \hat{x}_{aa} \geq 0$
b	$\hat{x}_b = -\hat{x}\frac{1}{b(c-1)} < 0$	$\hat{x}_{bb} = c\hat{x}\frac{1}{b^2(c-1)^2} > 0$
c	$\hat{x}_c = -\frac{ln(\hat{x})\hat{x}}{c-1} = \{c < 1,$ $\hat{X}_c > 0$ $c > 1,$ $\hat{X}_c < 0$	$\hat{x}_{cc} = \left[\hat{x}ln(\hat{x})\frac{2}{(c-1)^2} + \hat{x}ln(\hat{x})\frac{1}{(c-1)} + \frac{1}{c^2(c-1)^2} + \frac{1}{c^2(c-1)} + \frac{2}{c(c-1)^2}\right] > 0$

In table 5, we then synthesized how the composition of these three parameters might plot different functional forms. We refer to equation (1). This is the first generalization. It assumes that the exponent "c" might be different from 2, differently from what literature states. We can count more than ten theoretical functional forms. According to literature references, only three might represent waste income dynamics. We, therefore, plotted the main features. The most significant changes might be captured according to c variation. The assumption that is strictly equal to two is probably limiting. According to this premise, we established our approach of multiple FF or family approach.

Table of model tests

In this section, we shortly resumed table 6 for pre-selection tests. We tested for serial correlation (Breusch-Godfrey/Wooldridge), local cross-sectional dependence (Pesaran CD), Lagrange multipliers and their robust counterparts, five different Hausman tests, and finally, Honda tests for panel balance. Hausmann tests were divided into ML individual (1), time (2), and two-ways (3) effect then GM time (4) and individual (5). The tests have a null hypothesis of fixed effect inconsistency versus an alternative of random effects inconsistency. These tests are relevant as the convergence rate of our model is not high. Low convergence in estimation makes random effect regressors less efficient than fixed effect. In most articles we cited, both models are estimated. Local cross-sectional dependence represents a different definition of spatial dependence. The main purpose of the CD is to test dependence between observations. It can test global dependence without a spatial matrix or any weight matrix and local with one. We tested here for the second one with proof of presence. The difference with Moran I is the time frame. Pesaran CD can scope for local dependence across a timeline. The latter is strictly cross-sectional. To select the spatial lag, we used the Lagrange Multipliers. The robustness allows for ruling out possible individual effects. Despite a change in the magnitude of the p-value, we register no change in test results apart from Glass. Honda tests are used to rule out inefficient fixed effects. When the p-value is above 0.1, we will consider the treated effect as inefficient.

Table 13: All possible shapes that generalized FF takes.

	c = 0	0 > c > 1	c < 0	c > 1
a < 0 b < 0	Negative linear	Negative log	Negative linear	Exponential Negative
a > 0 b > 0	Positive linear	Positive log	Positive linear	Exponential Positive
a > 0 b < 0	Positive linear	"U" shape Fast turning	Hyperbolic 3rd, 4th with 1st quadrant	Inverted "U"
a < 0 b > 0	Negative linear	Inverted "U" Fast turning	Hyperbolic 2nd, 4th with 1st quadrant	"U"
a = 0 b > 0	No relation	Positive log	Hyperbolic 1st or 2nd quadrant	Exponential Positive
a = 0 b < 0	No relation	Negative log	Hyperbolic 3rd or 4th quadrant	Exponential Negative

Table 14: Model Selection tests

Test	Others	Paper	Organic	Wood	Metal	Plastics	WEEE	Selective	Textile	Glass	Recovered	Unrecovered	Total_MSW
Breusch-Godfrey/Wooldridge test for serial correlation in panel models	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***
Pesaran CD test for local cross-sectional dependence in panels	0***	0.7	0***	0***	0.043	0.002***	0***	0***	0.001***	0.003***	0***	0***	0***
LM test for spatial error dependence	0.097*	0.681	0.599	0.781	0.863	0.74	0.081*	0.348	0.046**	0.35	0.019**	0.113	0.174
LM test for spatial lag dependence	0.062*	0.022**	0.021**	0.397	0.078*	0.005***	0***	0***	0.317	0***	0***	0.978	0.234
Locally robust LM test for spatial error dependence sub spatial lag	0.746	0.033**	0.005***	0.148	0.004***	0***	0***	0***	0.017**	0***	0.001***	0.004***	0***
Locally robust LM test for spatial lag dependence sub spatial error	0.365	0.002***	0***	0.098	0.001***	0***	0***	0***	0.098*	0***	0***	0.017**	0***
Hausman test for spatial models	0***	0***	0***	0***	0***	0***	0.111	0***	0***	0.259	0***	0.985	0.713
Hausman test for spatial models	0.038	0***	0***	0.003***	0.677	0***	0***	0***	0.003***	0***	0.001***	0***	0.041**
Hausman test for spatial models	0.019**	0***	0***	0.005***	0.403	0***	0***	0***	0.002***	0***	0***	0***	0.261
Hausman test for spatial models	0.012**	0***	0***	0***	0.21	0***	0***	0***	0***	0***	0***	0.223	0***
Hausman test for spatial models	0.032**	0***	0***	0.008***	0.665	0***	1	0***	0***	0.633	0***	0***	0***
Lagrange Multiplier Test - (Honda) for balanced panels	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***
Lagrange Multiplier Test - time effects (Honda) for balanced panels	0***	0.022**	0.05*	0.008***	0.037**	0***	0***	0.007***	0.053	0.303	0***	0***	0.896
Lagrange Multiplier Test - two-ways effects (Honda) for balanced panels	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***	0***

Trends, AOG and Europe 1980-2020

AOG is expressed as a value with an interval of 0 and 1. It can be expressed as a percentage of total weight (stock-resource or waste-reserve), or grams per hundreds, thousands, etc. We classified elements according to expected returns from recycling (precious); relative rarity within EEE for potential recycling (rare); known poisonous impact on the environment (poisonous). In the end, we classified as neutral iron and chlorine: they were the only one to have no actual common characteristics with the others. Furthermore, they are the only ones to have a clear increase in recovery potential.

Stock AOG

According to the accessibility of recycling potential, we thought it would have been better to specify the resource one and the reserve one. For Resource potential, we thought to apply the AOG to the in-use stock of EEE. The term is taken in leas from extraction studies: total available resource comprises the available mass, due to techno-economic drivers, and the non-available one. Outside paying owners or thinking on possible schemes, the recyclable in-use stock has to reach terminal use, or in other words, maturity. It is possible to recycle waste, which in this study is considered reserve. This study does not aim to specify the flux limits due to recovering issues, landfill, or another process. AOG expresses a frontier rather than a real flux. We divided the estimates into five groups: rare, precious, poisonous, heavy, and neutral. The classification is not strictly relevant for scientific purposes.

Total in-use stock Potential

Total potential is the sum of all AOG currently estimated. It shows a rapid decrease in potential, probably due to the complexity of commodities and the rapid increase in the use of non-recyclable components. This change varies significantly across the *strata*. Similar patterns will be seen for the clustering of materials. We will see that materials have different recovery potential due to the *strata* level. Furthermore, this relation will vary for other reasons that will be hypothesis in intrinsic and extrinsic aspect.

Rare Elements

We ordered in this class the strategic elements of this panel within the EU mineral strategy. Antimony (Sb), Beryllium (Be), Bismuth (Bi), and Palladium (Pd) tend to have a decreasing AOG, with decreasing rate after 2000. Be is having a recent rehearsal for the lower *strata*. This change is relatively minuscule, given the almost null presence within the in-use stock.

Precious Elements

Precious elements appeared to behave similarly to rare ones. There is an overall reduction of ore grade. Nevertheless, the frontier for Gold (Au), Silver (Ag), and Copper (Cu) appear near the natural grade. This nearness would underpin recycling's positive performance, particularly for groups 3 and 4 of the

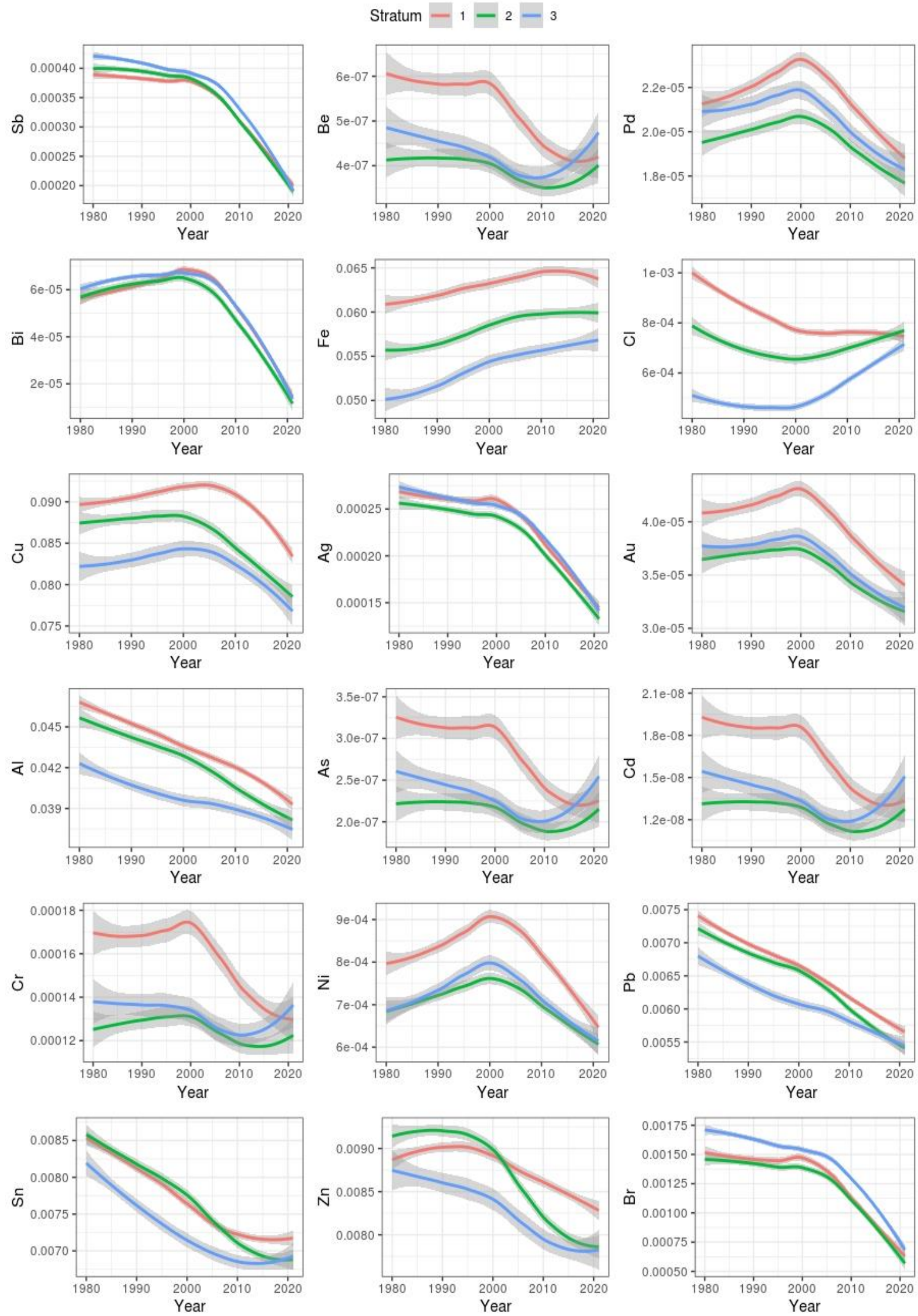

Figure 19: Stock-Resource AOG

WEEE EU 10 classification (Cucchiella et al., 2015). Furthermore, Aluminium (Al) had a lower reduction (around 10%) compared to Ag (almost 50%) and Au (around 20%). Still, Cu kept an even more stable path, losing less than 10% for all *strata*. Despite the reduction, we registered a small form of convergence for Al and Cu. AU and Ag potential reduce over time plainly over the *strata*. There was a noticeable peak for Au in 2000 for the richest countries.

Poisonous Elements

We collected within this class materials responsible for human poisoning. The stark difference with the other class is the apparent convergence of *strata* to one level. While the highest *stratum* has experienced a reduction, the other two are stable. The probable explanation is the demand structure within lower *strata*, which kept the same structure. On the other hand, Nickel (Ni) had a peak in 2000 while had a clear reduction concerning the start level.

Heavy Elements

Lead (Pb), Selenium (Sn), Zinc (Zn), Bromine (Br) are part of the heavy metal classification. In this, a stark reduction appears only for Br, reaching almost one-third of its initial levels. The others seem to stabilize in recent years, with similar trends for *strata* one and two. Of the categories, this is probably the most stable, with a high level of recovery potential.

Neutral Elements

We decided to call this class neutral as linked mostly with EEE in-use stock growth rather than in-use stock composition. Iron (Fe) appears to stabilize in recent years after an increase of 12% for *stratum* 1 and 17% for *stratum* three. It has the highest AOG of all panel materials due to the mix of efficient technology and high intensity in in-use stock. On the other hand, Chlorine (Cl) had an absolute convergence, rotating its vale between 1.25‰and 1‰. Given the constant technology matrix, *strata* 3 and 2 accumulated in time commodities that relatively reduce in *stratum* one.

Waste AOG

Total Waste AOG

The potential recovery within the estimated flux of waste generally decreases. The first *stratum* appears to ha a stable trend in recent years, around 30% of weight recovery. This value reaches a down-turning trend of less than 29% for the second *strata* and around 27% for the third one. In this case, the divergence in waste patterns seems evident. Ore grades vary greatly for each material too. This section will briefly review the changes in potential recovery according to the cohort of waste. As for the stock-reserve, we clustered the definitions according to rare, precious, poisonous, heavy, and "neutral" elements.

Rare Elements

Of the rare materials within EEE Stock, Antimony and Bismuth registered a peak in potential around 2000. Antimony seems to be more common in *strata* three waste and registered a peak a little after 1990, while *strata* one and two later near 2000. Bismuth to register a similar path. Nevertheless, it is almost equal in the potential for all countries. Palladium and Beryllium registered a general decrease, with a relative stabilization in recent years for the latter: the AOG value stands between 2 and 3 grams per million. Still decreasing, Palladium registered an AOG of 2.5-3 grams per ten thousand.

Precious Elements

Of four precious materials, silver, gold, and Aluminium have decreasing potential. On the other hand, copper seems to be stable for *strata* one with more than 10%. Other *strata* seem to register lower levels, generally less than 10%. Aluminum had decreased until 2000 when it started to stabilize around 5.5%. Within the flow of waste, we find that silver is more common than gold.

On the other hand, trends appear in both cases convergent around one value. Silver is present with 5.5-6.5 grams per 10000 in 1980 and around 4 grams per 10000. Gold started with 12 grams per 100000 and ended in 2020 with 8 grams per 100000.

Poisonous Elements

Arsenic, cadmium, and chromium registered a decreasing trend, with late stabilization. The potential recycling is higher in *stratum* 1 countries but is relatively rare: respectively 0.5 grams per million, 40 grams per billion, and less than 2 grams per thousands in 2020. On the other hand, Nickel registered a value of 2 grams per thousands, in slight change with 1980 of 2.5-3.5 per thousands.

Heavy Elements

Lead, Tin, Zinc, and bromide are relatively common compared to the other classes. Both lead and tin are steady for all *strata*, around 1.2 grams per hundred. Zinc AOG remained stable for *strata* 1 countries around 1.45 grams per hundred, while had a slight downturn in other *strata*, decreasing to less than 1.4 grams per hundred. At last, bromide had a peak point around 1995. The second *stratum* seems to be relatively richer, with an AOG of 2.25 per thousands in 2020.

Neutral Elements

As for stock-resource, waste-related neutral elements have increasing values AOG. Iron appears to register some form of divergence in recovery potential in 2020, but overall has the highest potential of all materials in waste. *Stratum* 1 countries have an AOG of more than 9%; lower *strata* countries registered an AOG between 7.5% and 8.5%. Chlorine has, on the other hand, a level of convergence of around 1.5 grams per thousands in 2020. The starting point was an interval between 2.75 grams per thousand for *stratum* 1 and 2 grams per thousand for *strata* 2, 3.

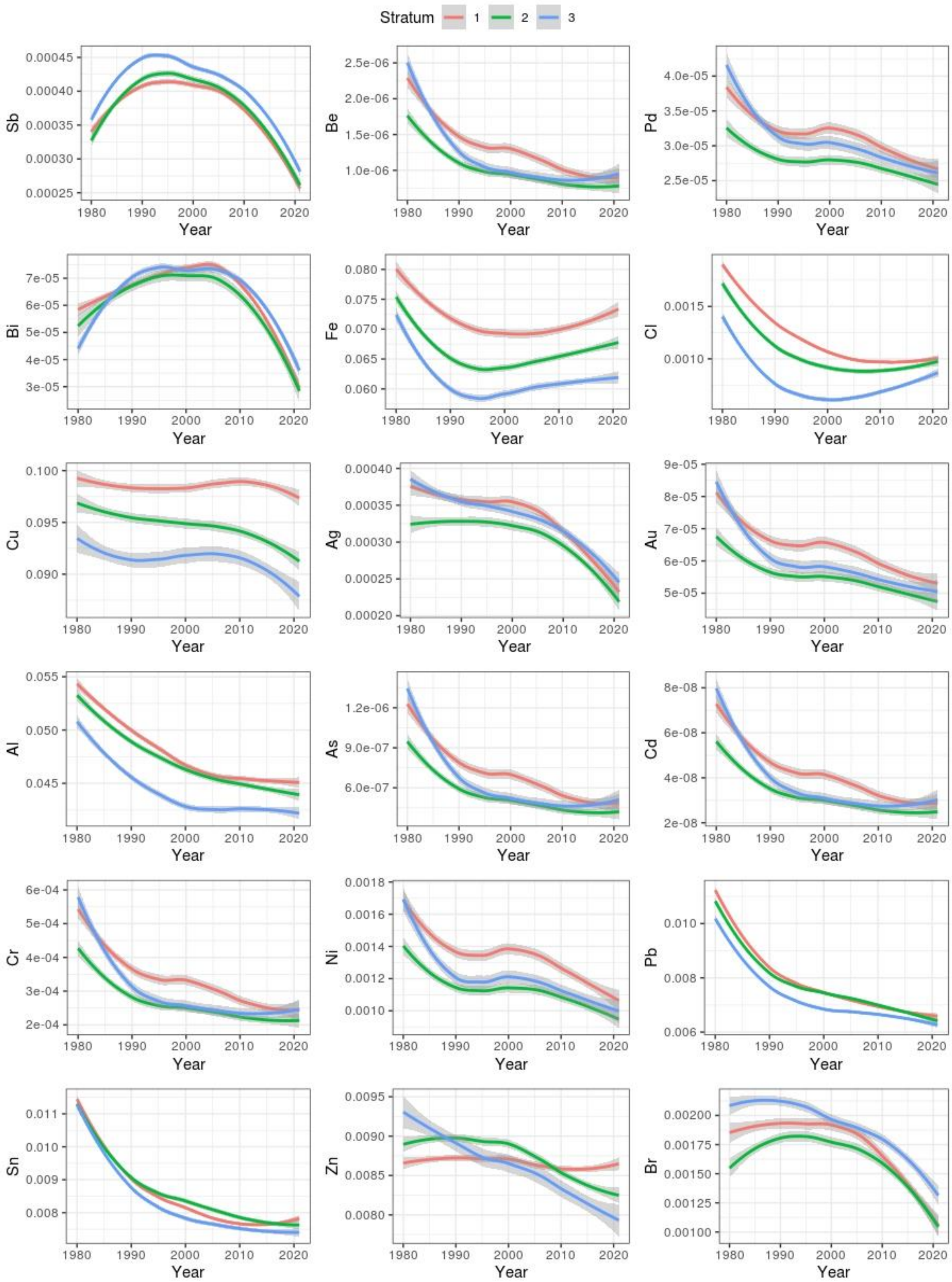

Figure 20: Waste/Reserves AOG

Nation	FE_{ref}	Fe_{EEE}	Cu_{ref}	Cu_{EEE}	Al_{ref}	Al_{EEE}	Ag_{ref}	Ag_{EEE}
AUT	16(1),9.5(2),	0.089	0.2(1)	0.010	0.324(2)	0.015	1(5)	0.000
BEL	11.2(2),	0.095	0.234(1)	0.011	0.38(2)	0.016	0.5(5)	0.000
BGR	2.2(2),	0.042	0.047(1)	0.004	0.075(2)	0.007	0.2(5)	0.000
CYP	12(1),5.4(2),	0.073	0.113(1)	0.007	0.183(2)	0.011		0.000
CZE	15(1),6.1(2),	0.000	0.129(1)	0.000	0.209(2)	0.000	0.3(5)	0.000
DEU	11.9(1),8.9(2),	0.003	0.2(1), 0.23(3)	0.000	0.324(2)	0.001	0.5(5)	0.000
DNK	12.2(1),8.7(2),	0.112	0.183(1)	0.013	0.289(2)	0.019	1.2(5)	0.000
ESP	8.80(1),7.2(2),	0.087	0.151(1)	0.009	0.245(2)	0.014	0.5(5)	0.000
EST	3.2(2)	0.064	0.066(1)	0.007	0.108(2)	0.011	0.25(5)	0.000
FIN	12.5(1),8.9(2),	0.095	0.189(1)	0.010	0.302(2)	0.016	1(5)	0.000
FRA	13.1(1),9.6(2),	0.087	0.202(1)	0.010	0.327(2)	0.014	0.5(5)	0.000
GBR	13.4(1),9.2(2),	0.105	0.194(1)	0.012	0.314(2)	0.018	1(5)	0.000
GRC	9(1),5.4(2),	0.075	0.113(1)	0.008	0.183(2)	0.012	0.2(5)	0.000
HRV	3.2(2)	0.053	0.067(1)	0.006	0.109(2)	0.009		0.000
HUN	6.7(1),4.4(2)	0.056	0.093(1)	0.006	0.15(2)	0.009	0.3(5)	0.000
IRL	7.1(1),9.5(2)	0.087	0.2(1)	0.010	0.324(2)	0.014		0.000
ITA	10.6(1),8.6(2)	0.090	0.18(1)	0.010	0.292(2), 0.31(4)	0.014	0.5(5)	0.000
LTU	2.8(2)	0.054	0.058(1)	0.006	0.095(2)	0.009	0.25(5)	0.000
LUX	13.3(2)	0.098	0.28(1)	0.011	0.453(2)	0.016		0.000
LVA	2.7(2)	0.047	0.057(1)	0.006	0.092(2)	0.007	0.25(5)	0.000
MLT	14.6(1),4.8(2)	0.071	0.101(1)	0.008	0.163(2)	0.011		0.000
NLD	10.2(2),	0.097	0.214(1)	0.012	0.346(2)	0.016	1(5)	0.000
POL	6(1),3.8(2)	0.045	0.079(1)	0.005	0.128(2)	0.007	0.33(5)	0.000
PRT	6.5(1),6.1(2)	0.078	0.128(1)	0.008	0.208(2)	0.012		0.000
ROU	6(1),2(2)	0.045	0.043(1)	0.005	0.069(2)	0.007	0.2(5)	0.000
SVK	4.4(2)	0.045	0.092(1)	0.005	0.148(2)	0.007	0.3(5)	0.000
SVN	5.4(2)	0.073	0.113(1)	0.008	0.184(2)	0.012		0.000
SWE	12.6(1),9(2)	0.093	0.189(1)	0.011	0.306(2)	0.016	1.2(5)	0.000

Table 15: (1) [Pauliuk et al., 2013], (2) [Rauch, 2009], (3) [Pfaff et al., 2018], (4) [Ciacci et al., 2013], (5) [Sverdrup et al., 2014], in tonnes per capita, Ag, Kg per capita

Capital growth to technological growth

The assumption of linear accumulation of R&D in a technological stock B implicates the proportionality of shadow prices. Recalling their co-state equations, we see:

$$\frac{\partial H_t}{\partial K_t} = \rho\lambda_t - \acute{\lambda}_t$$

$$\frac{\partial H_t}{\partial B_t} = \rho\mu_t - \acute{\mu}_t$$

If proportionality factor "η" is independent of time, we can derive F's control equation without changing the linearity condition. We changed signs with the time derivative of both terms of the identity. We multiplied both terms of the original identity by the discount factor "ρ".

$$-\acute{\lambda}_t = -\eta\acute{\mu}_t$$

$$\rho\lambda_t = \rho\eta\mu_t$$

By taking the vertical sum of the equation elements, we could trivially prove that co-state equations are proportional for "η":

$$\frac{\partial H_t}{\partial K_t} = \eta\frac{\partial H_t}{\partial B_t}$$

At this point, we inverted the terms leaving the proportionality factor on the right and multiplied both by the time derivative of the Hamiltonian function H:

$$\left(\frac{\partial H_t}{\partial K_t}\right)^{-1}\frac{\partial H_t}{\partial t} = \eta\left(\frac{\partial H_t}{\partial B_t}\right)^{-1}\frac{\partial H_t}{\partial t}$$

The resulting equation represents a transformation of technological growth. B and K growth are proportional. Thus, by substituting for technical growth equation, we can say that F is equal to K growth:

$$\acute{B}_t = \eta\acute{K}_t = \eta F_t \rightarrow \acute{K}_t F_t$$

Appendix 2: Equilibrium and stability

Our system involves three control variables and three state equations. Since specific research capital B is linearly explained by generic capital K, we can simplify the analysis to just one system. It to capital vs. consumption as described in equations 20 and 21. It reveals a mainstream solution of a saddle point. We constructed the Jacobian J[1] for the equations in such a way:

$$J^1(\dot{K},\dot{C}) = \begin{pmatrix} \frac{r}{3+d} & -1 \\ \frac{1}{\sigma_C}\bar{Y}_{KK} & 0 \end{pmatrix}$$

The solution is very similar to Ramsey–Cass–Koopmans model. Since steady-state consumption growth is null, J_{11} is zero. For production function concave to capital, the determinant is negative. According to the manifold theorem, since its eigenvalues have opposite signs, the system is a stable saddle point.

A caveat is required. The rate of decaying (and therefore substitution) "d" is influenced by goods durability. According to inflow-driven methodology, it can be estimated to follow a CDF of a Weibull. Its independent variable is the time of use. When a commodity reaches its natural limit, "d" should tend to one. Such interpretation of flows is used for data estimation and generates some complexities when modeling. The optimal condition would require that (1-d)ν tends to zero in the long-term. It is difficult to accept since shadow price "ν" would grow exponentially since M would be rigid to N at t*. In other words, since 1-d is zero after the "expiring date", whatever choice of N would not change M. Therefore, M shadow price would increase; the growth rate of "ν" would be higher than the speed of decaying, generating instability. This chaotic growth of "N" makes no sense according to the second law. We think this error could be explained by the exogeneity of net addition assumed by inflow-driven models.

$$\dot{M}_t = N_t - d_t N_t$$

These accounts were necessarily revised to be adequate for optimization. Considering the saddle point stability, we can conclude that any effort to achieve exponential growth would fail due to substitution. Hence, stock maturity and stability must be deterministically assumed.

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