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ASSESSING THE DEGREE OF "ISOLATION" OF A REGENERATIVE ECONOMY: THE COPPER CASE IN BRAZIL

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Table of Contents

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1 Intro

This paper quantifies the degree of "Isolation" of a specific substance within the economy with a Substance Flow Analysis (SFA). It then builds an Input-Output framework to analyse how the economic structure and the degree of "Isolation" are related where the SFA data is used. The copper flows within the Brazilian economy in 2008 are used as a case study where the SFA-IO framework is applied.

This paper provides a methodology to analyse and understand how to "Isolate" selected substances in order to achieve a Regenerative Economy. The Regenerative Economy concept (Altimiras-Martin 2012) is characterised by a specific arrangement of the material flows which mitigates systematically resource depletion and pollutant emissions. It is based on two principles: "Isolation" and "Integration". The "Isolation" principle is achieved by "strong-recycling", i.e. recycling substances such as metals and minerals so that they regain their original properties. "Integration" is achieved by integrating the extraction and release (restoration) of material flows from and to the corresponding biogeochemical cycles of the environment.

First, the paper describes the concept of the Regenerative Economy which is based at a theoretical level on two organisational principles: Isolation and Integration. The two organisational principles are translated in two corresponding operational principles: "strong-recycling" (which is the main subject of this paper) and "balanced extraction and restoration".

Then, this paper describes how to quantify Isolation at a material flow level with a SFA. It then develops an Input-Output (IO) framework able to use this information and model the degree of Isolation, i.e. stablish the relationship between the economic structure and the level of Isolation. The IO framework is based on the Waste Input-Output Analysis which traces in detail the reallocation of by-products and wastes within the economy (Nakamura and Kondo 2009). It then extends the WIOA framework by endogenising the household sector at both economic and material flow level. The developed framework also accounts for stock-in-use and the extraction and emissions from the different geospheres. Therefore, this framework provides a comprehensive picture of the material flows going through the economy.

Finally, this paper applies this framework to the case of copper in Brazil. So, it first develops the SFA of copper for the Brazilian economy in 2008 and then, it uses this data together with the monetary data of the same year.

The results show the current degree of isolation of copper in Brazil and therefore which flow paths could be modified in order to increase it. The technologies and sectors that need to be developed to modify the economic structure towards a Regenerative Economy will be discussed. The subsequent effects at a physical and monetary flow level will be simulated with the IO framework developed in this paper and discussed.

2 Previous considerations

2.1 The production-consumption structure

The Production-Consumption Structure (PCS) can be defined as the set of processes and infrastructure which extract, transform, use and dispose of the different materials within an economy. So, the PCS is a chain of processes linking producers and consumers within the established infrastructure. In other words, it is the underlying structure of the physical metabolism of an economy. A consequence of this approach is that production and consumption are intimately linked since what is produced is to be consumed and the way it is produced defines the way it is consumed.

The current production-consumption structure is linear. In other words, the economy works as a conveyor belt which extracts resources from the environment and returns them to the environment in the form of waste and pollution. For example, minerals and metals are mined, refined, transformed in components which are subsequently assembled in final goods, the goods are consumed and finally disposed and released back to the environment. Most materials are used in this manner.

Improving the efficiency of a process does not change the structure of the system even if it improves the overall system performance. If the efficiency of a link of the production-consumption chain is improved, the improvement spreads throughout the chain so the overall system will require less resources and pollute less. However, the linear structure of the system is maintained. Thus, even if at a lower rate, producing more goods will produce more pollution and waste.

Technological improvement (i.e. energy and resource efficiency improvements) have not managed to reduce in absolute terms the resource requirements of humans and resource extraction has consistently risen throughout this last century. Worldwide absolute resource extraction has increased eight times between 1900 and 2005 and the relative consumption per capita has doubled (Krausmann et al. 2009).

Technological improvement has neither managed to mitigate in absolute terms the emission derived from the use of the extracted resources. For example, carbon dioxide emissions have consistently risen in the same period (IPCC 2007). In the case of more harmful pollutants, End-of-Pipe (EoP) solutions has been employed to contain or divert their emissions, thereby mitigating their environmental impacts. For example, the emissions of sulphur derived from combustion of coal have been reduced through desulphurisation of flue gases in the power generation industry. However, EoP solutions do not change the Production-Consumption Structure, which remains linear. At worst, EoP solutions shift the problem away (i.e. the pollution is captured and released or stored in another place) and, at best, EoP solutions turn an emission or waste as a usable product (Ayres 1996).

Industrial Ecology has suggested other options than EoP solutions to mitigate the effects of pollution and improve the resource efficiency of the economy. Some of the suggestions, such as closing the material cycles (Ayres 1996) or Cleaner Production (Graedel and Howard-Grenville 2005) alter to some degree, for specific materials and processes, the production-consumption structure. However, there is no overarching strategy to systematically reorganize the material flows of the economy in a different production-consumption structure which mitigates resource extraction and pollutant emissions.

The Regenerative Economy concept presented in this paper suggest a possible overarching strategy to do so.

2.2 The Full-Recycling discussion

Full-recycling would drastically change the production-consumption structure/ metabolism of any economy. However, past interpretations of the extent to which this concept can be applied lead to some misunderstanding and cut the debate around this idea. This section shortly reviews those misunderstandings and shows that full-recycling systems already exist.

Georgescu-Roegen explored the physical limits of the economy by analysing the consequences of the 2nd law of thermodynamics for economic processes (Georgescu-Roegen 1971). He postulated two conclusions which cut the discussion on fully recycling economies. First, that the economy would degrade natural resources and the environment irreversibly due to the 2nd law of thermodynamics. Secondly, that full recycling is impossible due to the dissipative losses which happen in any process. The 1st statement is misleading because the earth is in fact an open system regarding energy and this energy can "compensate" the entropy loss. So, the Earth is not sentenced to degradation as long as energy from the sun is available. In fact, the renewable part of the environment (i.e. the biosphere) has survived millions of years by compensating the natural entropy loss in this manner. Why full-recycling is possible despite dissipative losses is explained in the next paragraph.

Ayres (1999) reviewed Georgescu-Roegen's work and he found that full recycling is possible. He demonstrates that a fully recycling system requires a specific structure with at least an intermediary "reservoir" where the dissipated material losses are accumulated so they can be recycled at a later stage. He made this demonstration thinking on the recycling of scarce industrial materials such as metals.

However, the description he did about a recycling system actually described to how the nature works. The different compartments of the system can be associated to natural reservoirs, and the different processes linking them correspond to the natural biogeochemical cycles. The biogeochemical cycles (BGCC) are the natural processes that transform and mobilise substances between the different parts of the environment (Butcher 1992; Bethke 2007). Industrial Ecology studies the inter-phase between industrial and natural processes but does not systematically study the BGCC which are studied in detail by the Earth System Science.

So part of the Earth System is an example of a fully-recycling system. Some biogeochemical cycles absorb energy from the sun to compensate the natural entropy losses. For example, the photosynthesis process fix energy that is subsequently degraded through the trophic chains. In other words, all living organisms constantly use and degrade energy, and thus require more energy. This energy helps then compensate their entropic loss. This energy has been in first instance fixed form the sun by the primary producers or autotrophs (i.e. photosynthetic organisms as plants).

An "almost" fully-recycling economy is feasible and would totally change the production-consumption structure. What Ayres (1999) calls dissipative losses are in fact pollutant and waste emissions. Therefore, as will be seen in the description of a Regenerative Economy, they are avoidable if the material flows within the economy are properly managed. Thus, dissipative losses can be reduced to negligible losses and therefore an "almost" fully-recycling economy can be achieved. This is the underlying idea of what will be called the Isolation principle of the Regenerative Economy. It is worth noting that some materials already follow this pattern in some industrial sectors (Graedel et al. 2011; Ayres 1996). Additionally, even if some losses are "unavoidable", they can be identified and managed so that the related emissions does not incur in any environmental impact. This is part of the underlying idea of what will be called the Integration principle. Those principles are the general principles which define the functioning of the Regenerative Economy and are described in section 3: The Regenerative Economy.

2.3 The Earth System

The Regenerative Economy can only be understood by contextualising the economy within the Earth System. It is therefore described below.

The Earth System can be compartmentalised in following 5 chemically homogeneous sections called the *geospheres:*

1. the *atmosphere* which is the gaseous envelope of the earth,
2. the *lithosphere* which comprises all rocks on (and under) the earth,
3. the *pedosphere* which represent the soils on the Earth's crust, covering the lithosphere in some parts of the Earth,
4. the *hydrosphere*, which represents all water, either in gaseous, liquid or solid form, and
5. the *biosphere*, which contains all living things and can be present in the any of the previous geospheres.

In this text, the term *environment* can refer to one or several geospheres.

The biogeochemical cycles (BGCC) are at the heart of the Earth System functioning. All geospheres transform and exchange materials flows with each other: those natural cycles are the BGCC. All materials in the earth system are linked through one or various BGCC. Different BGCC have different mobilisation/ transformation rates. The BGCCs can have different geographic scales, i.e. they can be local and/ or global.

Humans interact with the BGCCs in different manners: either by extracting (subtracting) materials from them or by releasing (adding) materials to them. These interactions lead to environmental degradation if the BGCC are altered beyond specific thresholds, i.e. when the extraction or release of substances affect the BGCC.

Some materials are considered isolated from the BGCC because the natural mobilisation or transformation rates of some substances are negligible for the time frame under study (a few hundred years). This is the case of substances isolated in natural reservoirs, usually within the lithosphere, such as oil/ gas pockets and metal ore seams.

There are three main types of materials:

Extinguishable and non-renewable materials such as hydrocarbons.

Extinguishable and renewable such as biomass. Biomass can be renewed indefinitely if the different cycles composing it are kept in balance. Otherwise, it can extinguish if a the BGCC regenerating it are disrupted. Therefore, biomass extraction has specific threshold levels above which the renewal is impaired and can lead to depletion (extinction) of the resource. For example when too much fisheries are caught, the fishery regenerates itself at lower rates. Therefore, extinguishable and renewable materials can potentially be fully-recycled (as long as a certain balance is kept). Depending on the degree of unbalance of the BGCC, the disturbance can cascade throughout other linked BGCCs. For example, the if the fishery is further extracted, it collapses and this affects the surrounding ecosystem.

Non-extinguishable and renewable such as minerals and metals. They are non-extinguishable because they are elemental substances which cannot be further decomposed (cannot extinguish). They are renewable since they can be renewed (cycled) through different reactions: e.g. metals can be oxidized and reduced in a cyclic manner, infinitely. Therefore, non-extinguishable and renewable materials can potentially be fully-recycled.

Emissions to the environment affect the BGCC through two different mechanisms.

Some materials are inherently toxic for certain parts of the environment. They are considered pollutants because they "disrupt" the BGCC (e.g. heavy metals and other persistent organic pollutants can cause a systematic collapse of some BGCC). However, there are other materials that are not toxic but can alter the natural functioning of specific BGCC when emitted or extracted in excess: they unbalance the BGCCs. For example, excess nutrients released in a water stream cause eutrophication problems – this is an unbalance of the Nitrate or Phosphate cycle. In general, thresholds levels are of the order of the natural flow, so for toxic emission they are very low since those substances are not naturally present in the BGCC while thresholds for non-toxic substances are much higher. Therefore, all substances emissions have also different thresholds above which they cause disruptions or unbalances in the BGCCs.

To summarise, the Earth System is a network of material flows from which humans (the economy) can extract and release materials to fulfil their needs. This interaction creates environmental degradation if the extraction and release unbalances or disrupts the natural BGCC, i.e. extract and/ or emit above certain thresholds.

3 The Regenerative Economy

The Regenerative Economy concept provides an overarching strategy to (re)organise the material flows of the economy in a specific production-consumption structure which mitigates systematically resource depletion and pollutant emissions.

3.1 Organisational principles: Isolation and Integration

There are two organisational principles that orchestrate the material flows of the Regenerative economy: the Isolation and the Integration principles.

The Isolation principle means that a specific substance is isolated within the economy. From the pollutant mitigation perspective, the benefits of isolation are straight forward: the substance is not released to the environment and therefore there the use of the substance does not lead to pollutant or waste emissions. There are two possibilities: the static one (linear accumulation) and the dynamic one (closed-loop circulation). The static approach to isolation means to isolate the substance by accumulating it in special landfills/ storages. This solution preserves the linearity of the PCS and is therefore of no interest here. The dynamic one means that the substance is (re)cycled constantly within the economy, avoiding storage issues. Hence, this solution requires a structural change of the PCS towards a cycling structure. In this case, resource requirements are systematically lowered due to the recirculation. The Regenerative Economy is interested in operationalising the latter which implies a closed-loop circulation of substances as a mean to Isolate them.

The Integration principle means that the material flows extracted by and released from the economy are integrated with the functioning of the Earth System. In other words, materials are extracted from and released to the environment at rates that respect its natural limits. The direct consequence of integration is that the interaction economy-environment does not cause environmental degradation due to the exchange of material flows, i.e. extraction of resources and release of emissions.

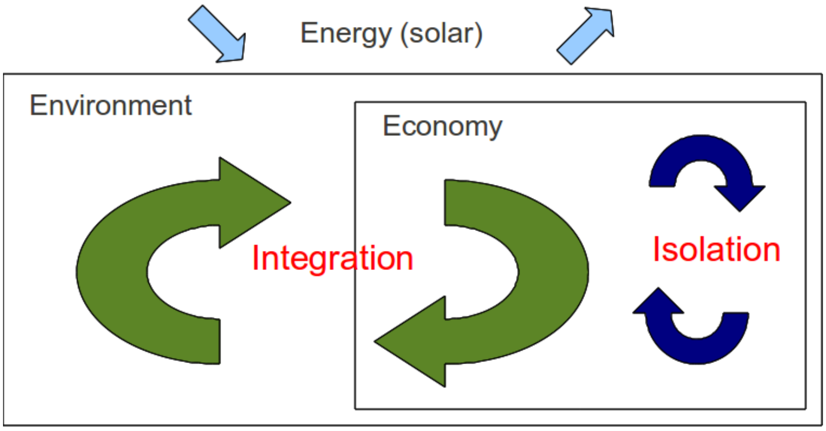

Illustration 3.1: Organisational principles of the Regenerative

To sum up, the Isolation preserves materials within the economy in a manner that can be reused indefinitely, cutting the extraction needs of the isolated material and maintaining the emissions to negligible levels regarding environmental pollution. The Integration principle allows other material flows to be exchanged with the environment without causing environmental degradation and subsequent depletion of renewable resources. Therefore, the rearrangement of the economy's material flows according to the Isolation and Integration principles provide a long-term strategy to cut current resource depletion and mitigate pollutant emissions.

The next section demonstrates the technical feasibility of the organisational principles by operationalising them.

3.2 Operational Principles

Each organisational principle is translated in an operational principle.

3.2.1 From Isolation to "Strong-Recycling"

Isolation is operationalised through the principle of "Strong-Recycling" which is opposed to conventional "recycling" practices. The aim of the Isolation principle is to isolate materials indefinitely within the economy through cycling. Indefinite cycling poses a constraint on the nature of the cycling : it cannot degrade the material to be cycled. So, the material need to be able to gain the original properties after being cycled through the economy or, in other words, it needs to be regenerated within the economy. Not all types of recycling match this requirement.

There are different types of recycling and not all comply to the non-degradation requirement. This is because the current definition of recycling is wide and covers very different recycling processes from a material flow perspective (European Parliament 2008). In fact, what is commonly known as "recycling" covers three different cases:

- materials that are recycled but degrade in the same recycling process. Therefore, the materials ultimately become waste after a few cycles (E.g paper).
- materials that are recycled as a different material. Thus, this can be done just once (e.g. glass when used as cement aggregate, or solid waste when incinerated).
- materials that are recycled as the same material without loosing its material properties (e.g. glass and metals when recycled as same material). This is the only case where materials are not degraded and preserve all their material properties after recycling.

The operationalisation of Isolation is based on the latter example of recycling, from now onwards called "Strong-Recycling".

A corollary is that not all materials can be strong-recycled but in most cases they can then be Integrated. This is discussed in section 3.2.3 Choosing between Isolation and Integration.

3.2.2 From Integration to "Balanced Extraction and Restoration"

The integration principle is operationalised by introducing the concept of biogeochemical cycles (BGCC) as a description of the Earth System. The Integration principle aims to re-arrange the exchange of material between the economy and the environment in a manner to avoid environmental degradation and subsequent renewable resource depletion. Recalling that the environmental degradation deriving from pollution is in fact due to the alteration of material flows of the environment which disrupt or unbalance the BGCCs, the integration principle can be operationalised by managing the exchange of material flows so that both extraction and emissions respect the BGCCs' thresholds, implying a balance in the material exchanges between the economy and environment. Hence, Integration is operationalised through the principle of "balanced extraction and restoration".

Additionally, the Balanced Extraction and Restoration principle has two dimensions, the local and the global.

The local dimension comes from the need of a *local balance* to avoid environmental degradation, i.e. in balance with the BGCCs in the local geosphere. The local balance implies that materials are extracted from or restored to the corresponding geosphere without causing any disruption or unbalance to the local BGCC during the very process of extraction or restoration. For example, the extraction of a fishery which allows enough time for the fishery to be repopulated is in local balance with the geosphere and related BGCC.

However, even if the extraction or restoration happen in local and momentary balance, it implies a constant subtraction or addition of materials which will eventually lead to local or global unbalance. The unbalance at local level can avoided if the materials are (re)balanced through linking BGCC globally.

Therefore, the local extraction and restoration must also be part of the *global balance* of the material flows which in turn restores the *local balance*. The *global balance* process between the local extraction and restoration of substances in different geospheres is achieved through a balanced linkage of the BGCC linking the local geospheres where extraction and restoration takes place. Such local-global-local cycling already happens naturally in the environment.

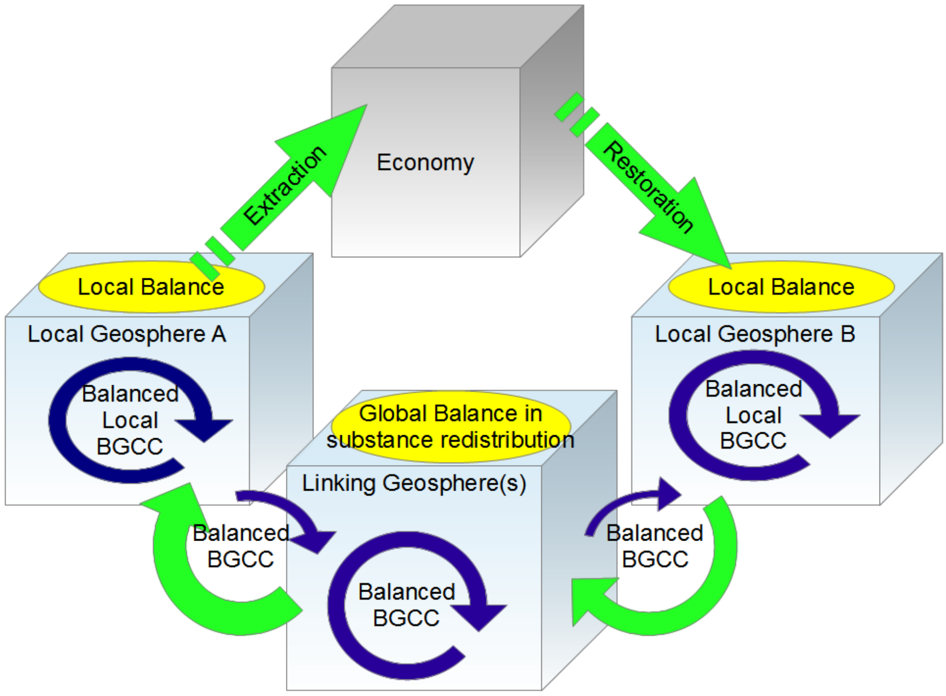

Illustration 3.2: Global and local dimensions of Integration

Therefore, a necessary condition for *global balance* is the mass balance through the different stages. In other word, the materials locally extracted by the economy must be equal to the materials locally restored. This is also true for the local geospheres. The extracted materials by the economy must be restored naturally in the same quantity by the corresponding BGCC. Similarly, the restored materials by the economy must be brought forward by same quantity the corresponding BGCC.

3.2.3 Choosing between Isolation and Integration

Whether a substance should or can be isolated or integrated depends on the nature of the substance and on the nature of its source. There are 3 main types of materials: extinguishable and renewable (e.g. biomass), non-extinguishable and renewable (e.g. elementary substances such as minerals and metals) and extinguishable and non-renewable (e.g. hydrocarbons). There are 2 types of sources: renewable ones (e.g. biomass and related non-biomass materials sources) and non-renewable ones which are in fact based on previous accumulation of non-extinguishable and renewable materials (e.g. mineral or metal seams), and extinguishable and non-renewable materials (e.g. coal seams or oil pockets). The non-renewable material sources are therefore extinguishable.

In order to achieve a materially sustainable use of materials, the following allocation between materials to the different principles is made.

On the extraction side, Isolation is required for non-renewable sources of materials which can be non-renewable and extinguishable materials or renewable and non-extinguishable materials. Both need to be isolated because otherwise the source would be eventually depleted.

On the emission side, Isolation is also required for the isolated (i.e. non-renewable) sources of materials. The emissions derived from isolated sources systematically unbalance BGCC since they are an absolute addition of substances to the bgcc (e.g. CO2 emissions from previously isolated (hydro)carbon reservoirs). Additionally, some emissions derived from isolated reservoirs disrupt some BGCCs because the emissions are toxic for some parts of the environment (e.g. heavy metals and persistent organic pollutants (POB) have ecotoxicity effects on some ecosystems).

On emission and extraction side, Integration is aimed at renewable sources of materials which are directly related to renewable and extinguishable such as biomass (and also indirectly to some renewable and non-extinguishable substances which ultimately compose biomass, e.g. carbon, nitrates, etc.). Renewable sources are the only sources where a balance between extraction and restoration of materials can be achieved. This requires the (synchronized) respect of the natural thresholds during extraction and restoration.

It is worth noting that it is also possible to Isolate materials coming from renewable sources (e.g. growing crops in a dome (Allen 1992)). This is usually costly in terms of energy (e.g. to supply to the energy that would be naturally absorbed from the sun) and in terms of infrastructure (to create the storage space where to grow the renewable resource). However, some of this possibilities might be considered when the substances could not be Integrated (e.g. because high crop productivity is required and required fertilizer flows could not be integrated in natural cycles). Also, some materials coming from isolated sources can be integrated to some extent with bioengineering techniques (e.g. some toxic heavy metals can be integrated in some biological cycles (Kothe and Varma 2011; Sherameti and Varma 2011)). This can be an alternative to Isolating some material flows but requires a deep knowledge of the BGCCs.

Substances can in fact be partially integrated and partially isolated, although at very different proportions. For example, some substances (e.g. copper) can be toxic when released above certain threshold in certain geospheres but are at the same time a basic constituent of biomass in extremely low quantities. The disproportion between natural and anthropogenic mobilisation rates has been shown by Baccini and Bruner (1991). For simplification purposes, this text does not consider the integration of non-extinguishable and renewable materials.

To sum up, as a general guideline, renewable and extinguishable materials (i.e. biomass) are to be Integrated, and renewable and non-extinguishable materials which are not directly related with biomass are to be Isolated. Non-renewable and extinguishable materials such as hydrocarbons are not to be used unless Isolated.

	Isolation	**Integration**
System definition	Economy	Economy-Environment
Organisational concept	"Almost" Full-recycling Within the economy	Full-recycling Between economy and environment
Operational principle	Strong-recycling	Balanced extraction and restoration
Materials related to the extraction of:	Non-renewable resources	Renewable resources
Materials related to the emission of:	Toxic substances	Non-toxic substances
Material type	Non-renewable/ extinguishable And Renewable/ non-extinguishable	Renewable/ extinguishable and directly related renewable/ non-extinguishable

Table 1: Summary table of the Regenerative Economy concept

From now onwards, a Regenerative Economy is simplified as follows: non-extinguishable and renewable materials from non-renewable resources are Isolated, extinguishable and renewable materials from renewable resources are Integrated (together with the associated non-extinguishable and renewable materials), and extinguishable and non-renewable materials are not used.

Hence, the Regenerative Economy relies on implementing the technologies which allow to substitute materials and processes so that the material flows are either Isolated or Integrated. So, the Regenerative Economy restructures the current linear structure towards a structure which *isolates* some material flows within the economy and *integrates* the other material flows with the different biogeochemical cycles which compose the environment. In other words, part of the materials are (almost) fully-recycled within the economy by "strong-recycling", avoiding resource extraction and pollutant emissions. The other materials are recycled throughout the different biogeochemical cycles thanks to a "*balanced extraction and restoration*" of the material flows, avoiding the depletion of renewable resources and the degradation the environment because the biogeochemical cycles are preserved.

4 Characterising and Quantifying Isolation

4.1 The material flows of the Regenerative Economy

This section translates the operational principles in a generic material flow classification which are the basis to quantify the degree of Regeneration of the Economy (i.e. the degree of Isolation and Integration). The inputs and outputs of the economy as a whole and of every economic sub-process can be classified generically in the following five types.

1. Controlled inputs: inputs which satisfy the operational principles.
2. Uncontrolled inputs: inputs which do not satisfy the operational principles.
3. Controlled outputs: outputs which satisfy the operational principles.
4. Uncontrolled outputs: outputs which do not satisfy the operational principles.
5. (Controlled) Dissipative outputs: dissipative losses associated to controlled outputs which are Integrated. Note that Uncontrolled Dissipative losses are included in the uncontrolled outputs.

However, the Isolation happens within the economic system, so it can be characterised by the interaction between the economic sub-processes alone (i.e. between the economic sectors). So, to identify the Isolated flows, the five material categories can be restricted as follows when:

1. Controlled inputs are inputs that come from another economic sector.
2. Uncontrolled inputs are inputs which come from the environment.
3. Controlled outputs are inputs that go to another economic sector.
4. Uncontrolled outputs are outputs which go to the environment.
5. (Controlled) Dissipative outputs: dissipative losses associated to controlled outputs which are Integrated, i.e. do not unbalance or disrupt BGCCs. Note that Uncontrolled Dissipative losses are included in the uncontrolled outputs.

This text is not interested in quantifying Integration so its definition in terms of material flows is not developed here.

4.2 Characterising full Isolation

The previous section has explained how a Regenerative Economy can be explained in terms of material flows. This section defines Isolation in terms of the previously defined material flows.

At economic level, a specific substance can be said to be fully Isolated when the inter-industrial flows, given a steady consumption and population, comply to the following criteria for each economic process:

1. controlled inputs = controlled outputs
2. uncontrolled inputs = 0
3. controlled outputs = controlled inputs
4. dissipative outputs = negligible and do not affect BGCCs.
5. uncontrolled outputs = 0

This means that taking the economy as a whole and given a steady consumption and population, the material flows are as follows:

1. extraction = 0
2. emissions = 0
3. dissipative outputs = negligible and do not affect BGCCs.

However, the classification on its own does not inform of how the materials flow through the economy. So, it is not clear how the uncontrolled inputs or outputs affect the degree of Isolation. Hence, it is necessary to use an indicator or how those cycles flow within the economic system, i.e. which materials cycle and to which extent.

The chosen cycling indicator is the Finn cycling index (FCI) (Finn 1976) which provides a measure of the level of cycling within a defined system. It is the fraction of the total cycling flows through the system expressed as a ratio to the total straight flows (FCI = cycling flows / straight flows). It therefore ranges from 0 (no cycling at all) to an arbitrary large number (cycling flows overwhelming straight flows). So, the higher the FCI, the closer to full Isolation. Therefore, the Finn Cycling Index has no unit and allows to compare different systems although the average path length and FCI are sensitive (or even a function of) the number of compartments (i.e. economic sectors) of the system.

The characterisation of Isolation will be complemented by the decomposition of the Leontief matrix between the cycling and noncycling material flows of the economy using the method devised by Han (1997).

4.3 Quantifying the material flows with SFA

A Substance Flow Analysis (SFA) provides the picture of the use, transformation and transportation of a specific substance (or a limited group of substances) within a system for a defined timespan. In other words, the SFA consists in finding and quantifying the different pathways of a substance through a system. In this case the system is the economy itself so, under an SFA perspective, the economy can be seen as a network of material flows of the substance under analysis.

The SFA methodology differs from the bulk-MFA one. SFA is focussed on a single substance and therefore allows to address specific industrial or environmental issues associated with the use or emissions of that substance. On the other hand, bulk-MFA studies aggregate materials in order to obtain macro economic indicators (OECD 2008a; OECD 2008b; OECD 2008c).

The SFA differs from Life-Cycle Analysis in that it does not necessarily go through the whole life cycle of a product. Instead, it traces the substance (and derived emissions) within the defined geographic system and time-frame which do not necessarily include all the life cycle of the substance or product.

SFA is the chosen method to quantify Isolation (and Integration) because traces accurately the substance flows within a given (economic) system. The SFA performed on this paper focusses on identifying the dissipative losses from other emission types.

In this paper, the SFA system definition is a national economy and its interactions with the national environment within the national geographic boundaries. The time-frame is a year. Both are consistent with the system definition of the System of National Accounts (SNA) which focusses as well on a specific country for a year.

The SFA would provides the information on how a substance is:

- extracted from the environment

- used within the economy, i.e. transformed and mobilised within the different industrial sectors and final demand sectors,
- released back to the environment, either in form of emissions or waste.

The SFA is based on the study of products and emissions that contain the substance and processes and the processes that transform and mobilise those products. Those substance flows can therefore be allocated (and aggregated) to the corresponding economic sector creating a map of the flows of the substance within the economy, i.e. between the different sectors. The SFA would then reveal how much of the substance flows between the environment, the extraction sectors, productive sectors, manufacturing sectors, household sectors, government sector and how much is emitted them in form of waste and emissions and where does this waste and emissions go.

Additionally, the SFA to quantify Isolation needs to provides information about:

- the emissions derived from the stock-in-use because such emissions can be significant and would mean that the substance is not isolated within the economy.
- The type of flows: whether emissions are dissipative, uncontrolled or controlled.

5 Modelling Isolation with Input-Output Analysis

In order to model the relation between the degree of Isolation and the economic structure, the Input-Output (IO) framework needs to:

- Account for the reallocation (i.e. recycling) of wastes, emissions and byproducts within the economy. This is done by using a Waste Input-Output Analysis (Nakamura and Kondo 2009) introduced below,
- Account for the emissions related to the use of products and represent the internal functioning of the economy, i.e. as a whole structure including both producers and consumers. For both reasons, the HouseHold (HH) sector is endogenised. Closing the model for HH allows to assess the consumption and derived emissions of non-durable goods and assess different material consumption behaviours.
- Account for the different types of material flows exchange between the economy and the environment. This is done by extending the IO framework with the different types of material flows (extraction, emissions and dissipative losses) extracted from and emitted to each geosphere.

5.1 Basics of Waste Input-Output Analysis

The Waste Input-Output Analysis (WIOA) is a framework which focuses the waste and emissions cycles, allowing an explicit and detailed characterisation of the reallocation of waste amongst inter-industrial and waste-treatment sectors. It is an extended abatement model which allows to account for several by-products simultaneously for a single sector. This framework treats wastes as by-products. The production and reallocation of the by-products is based on a (Waste) Make and Use matrix built for the by-products. This matrix allows to characterise the full life cycle of the materials within the economy, i.e. to explicitly characterise the reallocation between waste/ by-product producers and other sectors which reuse/ recycle those products including the waste treatment sectors. This framework is in sharp contrast with the Leontief abatement model which requires a 1-to-1 correspondence between the waste type and abatement sector. The Leontief abatement model cannot account for the treatment of the pollution in such a comprehensive manner, i.e. reallocating several waste types amongst several sectors.

The WIOA is based on an *n* sectors inter-industrial monetary Input-Output Table (MIOT) called A_I (nxn). The inter-industrial matrix is extended with *k* specific waste-treatment sectors and creates the A_{II} matrix (nxk). The industrial, waste treatment and final demand sectors can produce *m* by-products (which are in fact by-products, wastes or emissions). The production of by-products correspond to the following "make matrices": W_I^{out} (mxn), W_{II}^{out} (mxk) and w_f^{out} (mxl). The (re)use (i.e. reallocation) of the produced by-products is given by the corresponding "use matrices": W_I^{in} (mxn), W_{II}^{in} (mxk) and w_f^{in} (mxl).

The matrices W^{out} and W^{in} are key in the life cycle characterisation since they display which sectors produce by-products (i.e. wastes and emissions) and which sectors re-use them. This method automatically allocates the "unused" (or "excess") by-product for disposal in the corresponding waste treatment sector. This is an important feature of the WIOA since it avoids the issue of obtaining negative values for final demand when by-product producion is higher than its demand.

The W^{out} and W^{in} matrices are also important for ensuring mass balance in inputs and outputs of the economic sectors.

The WIOA framework is as follows:

		Economic Sectors				**Waste treament sectors**			**Final Demand**		
		s_1	s_2	…	s_n	WTS_1	…	WTS_k	FD_1	…	FD_l
Economic Sectors	s_1	A_I				A_{II}			f		
	s_2										
	…										
	s_n										
By-product generation	w_1	W_i^{out}				W_{II}^{out}			w_f^{out}		
	…										
	w_m										
By-product use	w_1	W_i^{in}				W_{II}^{in}			w_f^{in}		
	…										
	w_m										

The production and use of the by-products and wastes can be aggregated in a single Waste (by-product) matrix $W = W_I^{out} - W_I^{in}$ in which positive values refer to produced wastes and negative to used wastes. The resulting matrix embeds the reallocation of each waste type amongst the different economic and waste-treatment sectors.

At this point, the different waste types can be allocated to the corresponding treatment sectors. In fact, the waste-treatment sectors will effectuate the treatment on the "unused" by-products, not on the whole production of it since some sectors use of part of the produced wastes. The reallocation of by-products amongst the different sectors happens according to the technologies and practices available in the economy, which are represented by an allocation matrix S (k x m). The squared industry-industry matrix is derived by multiplying the allocation matrix by the different Waste matrices and vector (W_I, W_{II} and w_f).

		Economic Sectors				**Waste treament sectors**			**Final Demand**		
		s_1	s_2	…	s_n	WTS_1	…	WTS_k	FD_1	…	FD_l
Economic Sectors	s_1	A_I				A_{II}			f		
	s_2										
	…										
	s_n										
Waste treament sectors	WTS_1	SW_I				SW_{II}			Sw_f		
	…										
	WTS_k										

So, in terms of data requirement, the WIOA does not need a full physical input-output table but only a the physical make and use matrices of the by-products produced and used by the different industrial and waste management sectors . The inter-sectoral matrix stays in monetary terms. The data for the by-product production and use can be obtained from different sources or specially produced by a SFAs.

5.2 Endogenising the household sector

Endogenising the household sector is mandatory in order to represent the functioning of the production-consumption structure (i.e. metabolism) of the economy. In open IO models the household sector is out of the model boundaries and its role in the material use and discard process cannot be characterised. Therefore, the framework developed in this paper closes the Waste Input Output framework for the household sector in order to account for the role of the household sector as part of the metabolism of the economy, both in terms of materials consumed (final goods) and materials emitted (waste and emissions).

The HH sector is endogenised within the inter-sectoral matrix A_I a (see Miller and Blair (2009, chap. 2.5) and obtain $\hat{A}_I$ as follows:

$$\tilde{\mathbf{A}}_I = \begin{bmatrix} \mathbf{A}_I & \mathbf{h}_c \\ \mathbf{h}_R & 0 \end{bmatrix}$$

where $\tilde{\mathbf{A}}_I$ is the new inter-sectoral matrix with households endogenised, $\mathbf{h}_c$ is the household consumption vector, $\mathbf{h}_R$ is the row vector of labour input coefficients. Regarding the WIOA, the waste matrix W_I is correspondingly expanded to $\hat{W}_I$ by adding a column for household production and use of waste and by-products.

So far, the IO framework follows the scheme below:

		Economic Sectors					**Waste treament sectors**			**Final Demand**
		s_1	s_2	…	s_n	HH	WTS_1	…	WTS_k	FD
Economic Sectors	s_1	$\hat{A}_I$					A_{II}			f
	s_2									
	…									
	s_n									
	HH									
By-product generation	w_1	$\hat{W}_i^{out}$					W_{II}^{out}			w_f^{out}
	…									
	w_m									
By-product use	w_1	$\hat{W}_i^{in}$					W_{II}^{in}			w_f^{in}
	…									
	w_m									

The allocation matrix remains unchanged because the number of waste types and waste-treatment sectors are unchanged. The inter-sectoral matrix can be found through the allocation matrix (S) as before.

		Economic Sectors					**Waste treament sectors**			**Final Demand**
		s_1	s_2	…	s_n	HH	WTS_1	…	WTS_k	FD
Economic Sectors	s_1	$\hat{A}_I$					A_{II}			f
	s_2									
	…									
	s_n									
	HH									
Waste treament sectors	WTS_1	$S\hat{W}_I$					SW_{II}			Sw_f
	…									
	WTS_k									

However, the column for household emissions represent only the emissions derived from the consumption of non-durable goods. In each period, households consume non-durable and durable goods. All non-durable goods are consumed within the period and the subsequent emissions are accounted correspondingly in that period. The durable goods (buildings, vehicles, infrastructures) can also release emissions. Those emissions will be accounted in a special category called stock-in-use, as described below.

5.3 Stock-in-use

The stocks-in-use are also included in the IO framework since they can be an important source of emissions. Emission can be due to the use of the stock-in-use or simply by wearing of the stock.

To represent the production-consumption structure consistently, the Stock-in-use is disaggregated between the stock-in-use of the household sector and the rest of sectors.

Stock-in-use can release emissions directly to the environment, however it does not produce (nor use) emissions within any economic activity because this type of emissions are already embedded in the corresponding economic activity. For example, a metallic structure needs maintenance and as a result a part of it is changed and some metal scrap is produced. The metal scrap production is not allocated to the stock-in-use, but to the sector performing the maintenance. The emissions of the stock-in-use are only directly due to its use. For example, the metallic structure corrodes and consequently releases part of its mass to the environment as oxidized substance.

The data informing of this kind of emissions can be obtained by the SFA.

Note that the stock-in-use accounting is different from the variation of stock (which is to balance the production and consumption for the current period).

Even if stock-in-use are quantified the developed framework is static (i.e. non dynamic).

		Economic Sectors					**Waste treament sectors**			**Final Demand**	**Stock-in-use**	
		s_1	s_2	…	s_n	HH	WTS_1	…	WTS_k	FD	HH	Other
Economic Sectors	s_1	$\hat{A}_I$					A_{II}			f	$Stock_{HH}$	$Stock_{Oth}$
	s_2											
	…											
	s_n											
	HH											
By-product generation	w_1	$\hat{W}_i^{out}$					W_{II}^{out}			w_f^{out}	0	0
	…											
	w_m											
By-product use	w_1	$\hat{W}_i^{in}$					W_{II}^{in}			w_f^{in}	0	0
	…											
	w_m											

The allocation matrix remains unchanged because the number of waste types and waste-treatment sectors are unchanged. The inter-sectoral matrix can be found through the allocation matrix (S) as before.

		Economic Sectors					**Waste treament sectors**			**Final Demand**	**Stock-in-use**	
		s_1	s_2	…	s_n	HH	WTS_1	…	WTS_k	FD	HH	Other
Economic Sectors	s_1	$\hat{A}_I$					A_{II}			f	$Stock_{HH}$	$Stock_{Oth}$
	s_2											
	…											
	s_n											
	HH											
Waste treament sectors	WTS_1	$S\hat{W}_I$					SW_{II}			Sw_f	0	0
	…											
	WTS_k											

5.4 Extension with geospheres

The IO framework is further extended with generalized input and output coefficients for the resource extraction and pollutant emissions. In other words, we assume that the extraction and emission rates vary linearly with sectoral outputs. The extraction and emission of the substance(s) is disaggregated to represent the material exchange with the different geospheres.

According to the discussion on material flow types, the emissions are further classified in three types: extraction (Ext), emissions (E) and dissipative emissions (DE). The data on the corresponding physical flows is obtained by the SFA.

The resulting framework to assess the degree of the Isolation is as follows. Note that the stock-in-use can also fix (i.e. extract) substances from the environment. The SFA will however consider those negligible, i.e. zero.

			Economic Sectors					**Waste treament sectors**			**Final Demand**	**Stock-in-use**	
			s_1	s_2	…	s_n	HH	WTS_1	…	WTS_k	FD	HH	Other
Economic Sectors		s_1	$\hat{A}_I$					A_{II}			f	$Stock_{HH}$	$Stock_{Oth}$
		s_2											
		…											
		s_n											
		HH											
Waste treament sectors		WTS_1	$S\hat{W}_I$					SW_{II}			Sw_f	0	0
		…											
		WTS_k											
Emissions	to pedosphere	Urban/industrial	E_I					E_{II}			E_f	$E_{stock\text{-}HH}$	$E_{stock\text{-}Oth}$
		Agricultural											
		Other											
	to atmosphere	Urban/industrial											
		Agricultural											
		Other											
	to hydrosphere	rivers											
		aquifers											
		Sea											
Dissipative Emissions	to pedosphere	Urban/industrial	DE_I					DE_{II}			DE_f	$DE_{stock\text{-}HH}$	$DE_{stock\text{-}Oth}$
		Agricultural											
		Other											
	to atmosphere	Urban/industrial											
		Agricultural											
		Other											
	to hydrosphere	rivers											
		aquifers											
		Sea											
Extraction of resources	from pedosphere	Urban/industrial	Ext_I					Ext_{II}			Ext_f	0	0
		Agricultural											
		Other											
	From atmosphere	Urban/industrial											
		Agricultural											
		Other											
	From hydrosphere	rivers											
		aquifers											
		Sea											

5.5 Data requirements

The developed framework is based on monetary and physical data.

This monetary flows can be derived from the SNA of the country where the A_I matrix of inter-sectoral monetary flows is usually readily available. $\hat{A}_I$ can be built as well with that information. The inter-sectoral matrix needs to be further disaggregated for the different waste-treatment sectors which are usually not readily available. The corresponding sector in the inter-industrial matrix must be correspondingly disaggregated.

The physical flows for extraction can be found in the statistical reports for different sectors, e.g., mineral and agricultural extraction statistics are well established. However, the extraction of specific substances require further processing of that information. The SFA can provide this information consistently.

The physical flows for pollutant and waste emissions are, with some exceptions, not available in a consistent manner. Some emissions are well accounted and are part of the national System of Environmental Accounts (SEA). Also, some toxic substances are included in national Pollutant Release and Transfer Register (PRTR). However, SEA and PTRT does not necessarily provide accurate information on the sector or geosphere where the emission comes from or is released to. Also, even if some general statistics on waste generation are available for some sectors and types of waste (Municipal Solid Waste (MSW), Waste Electric and Electronic Equipment (WEEE)), those do not provide fine information on the substances composing it. Therefore, a detailed analysis such as a SFA is required in order to provide the information on emissions required to quantify isolation. However, the SFA requires a general assessment of the substance flows exchanged within the economy. Hence, even if only the production and use emission is required for the IO framework, all the substance flows within the economy will be characterised.

The SFA performed in this paper reveals the material flows of the specific substance within the economy and between the economy and the environment. Specifically, it quantifies the amount of the substance present in goods and infrastructure, emissions and waste produced and used by each sector.

The SFA results are aggregated according to the productive structure and match the economic sectors as defined in the IO framework. In this case, the flows can be aggregated under the extraction, production, manufacturing, consumption and waste-treatment sectors.

The developed IO framework is based on the national Monetary Input-Output Table (MIOT). However, Physical Input-Output Tables (PIOTs) are required for characterise the emissions and reuse of by-products. The SFA supplies the information to create the PIOT for the specific substance.

Also, the SFA determines the amount of stock-in-use and its derived emissions.

5.6 Summary of the framework

The developed IO framework allows to quantify the degree of Isolation and relate it to the production-consumption structure (i.e. metabolism) of the economy. It allows to identify which sectors are strong-recycling so the degree of Isolation can be determined. It also identify which sectors are releasing emissions to the environment so it can be suggested how to (strong-)recycle those emissions.

The main characteristics of the framework are:

1. Based on the Waste Input-Output Analysis
2. Closed for (endogenisation of) the household sector to assess the production-consumption structure (i.e. metabolism) as a whole.
3. Closed for the stock-in-use to accurately represent dissipative losses and therefore quantify accurately Isolation. The stock-in-use are disaggregated between the ones from households and other sectors.
4. extended with extraction from and emission to the different geospheres. The emissions are further disaggregated between Emissions and Dissipative Emissions.

6 Empirical application

This paper makes the empirical application of the framework described above for the case of copper in Brazil. Copper is a perfect candidate for Isolation because:

1. it can be strong-recycled since it is a metal, i.e. a non-extiguishable and renewable material.
2. emissions of copper are toxic and can only be managed by isolating them from the environment[2].
3. copper is an important resource for societies which can be depleted (Gordon, Graedel, and Bertram 2006). Therefore it is important to preserve its resources and specially the stock-in-use already present in the economic system.

6.1 Copper SFA for Brazil

The structure of the SFA draws on Tanimoto et al. (2010) which completed an SFA for copper SFA for Brazil in 2005 which quantifies:

- extracted copper and derived waste
- produced copper and derived emissions and waste
- manufactured copper and derived emissions and waste
- copper used by households and derived emissions and waste (this include the use of non-durable goods and of the stock-in-use which refer to the durables).
- waste-treatment and its emissions and waste

This analysis will be updated for copper flows in 2008 to match the IO data.

However, the analysis will be extended to disaggregate the stock-in-use between the household and other sectors and quantify the corresponding emissions.

Also, the SFA will be extended to account for the material flows exchange with each geosphere.

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[2] This is not strictly true since there are small amounts of copper presents in living organisms and hence some copper flow could also be integrated. Those are negligible quantities compared to the uncontrolled or even dissipative emissions of copper. The framework developed in this paper is not prepared to assess Integration.

6.2 Developing the IO framework for Brazil

The latest MIOT available for Brazil is from 2005 (IBGE 2012). The 2008 MIOT will be estimated according to Guilhoto and Sesso Filho (Guilhoto and Sesso Filho 2005; Guilhoto and Sesso Filho 2010). It is a 56x56 matrix which will be disaggreagated with three extra waste-treatment sectors: landfilling, shredding and incineration.

The household sector will be endogenised with 3 material consumption groups with specific buying, use and discard patterns (which correspond to 3 rent level groups). The information about the structure of consumption is estimated from the Pesquisa de Orçamento Familiar 2008-2009 (POF) (IGBE 2009) and the income distribution from the Pesquisa Nacional por Amostra de Domicilios (PNAD) (IBGE 2009).

The physical flows of copper by-products (wastes) derived from each sector and their reallocation to other sectors or waste-treatment, the extraction of copper from the environment, the emissions of copper to the environment and the stock-in-use are provided by the SFA.

7 Sectoral analysis and discussion

The framework provides a picture of the current degree of Isolation of the Brazilian economy regarding copper. It reveals which sectors are emitting (leaking) copper in the environment. Different solutions to isolate copper at a higher degree will be suggested, e.g. by suggesting which technologies or sectors can be further developed in other to completely recycle copper. The effect of those changes on the economic structure will be assessed.

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