Energy, Materials, Information. How to define a Circular Thing.

Energy, Materials, Information

How to define a *Circular Thing*

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"Energy, Materials, Information.
How to define a Circular Thing"

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Author's preface

The 16th of September 2015, *Nature* scientific journal titled "Interdisciplinarity", a special issue dedicated to the rise of interdisciplinary collaborations to solve world's biggest problems. In spite of the recent emergence and call for interdisciplinary research, the necessity of collaborations among two, or more, disciplines to face the global challenges, the so-called *grand challenges*, was already known since decades (Gibbons, 1994). In the Eighties, as reported in the special issue, Theodore Brown, to convince an investor to fund the research of the University of Illinois, said *"the problems challenging us today, the ones really worth working on, are complex, require sophisticated equipment and intellectual tools, and just don't yield to a narrow approach. The traditional structure of university departments and colleges was not conducive to cooperative, interdisciplinary work".* More recently, an educational psychologist, continued (Ledford, 2015)

> *"the problems in the world are not within-discipline problems ... We have to bring people with different kinds of skills and expertise together. No one has everything that's needed to deal with the issues that we're facing".*

Following the debate, recently Bosch (2018), again in *Nature*, titled "Train PhD students to be thinkers not just specialists" a controversial article regarding Ph.D. scholars and their training. In the opening of the article, the author highlighted that *under pressure to turn out productive lab members quickly, many PhD programmes in the biomedical sciences have shortened their courses, squeezing out opportunities for putting research into its wider context.* In the last decades interdisciplinary research gained its momentum and spread all around the world, boosting fruitful academic collaborations (as the recent art&science convergence). Hundreds of researchers targeted interdisciplinary collaborations in order to understand pros and cons and their functioning (Okamura, 2019). Scientists, historians, philosophers of sciences, since the groundbreaking book *The structure of scientific revolutions* of T. Kuhn, are struggling to understand how new scientific paradigms emerge. Only recently, thanks to new data science tools and the large availability of open data, this fundamental question encountered a precise answer. In October 2020, a new preprint titled "The network structure of scientific revolutions" appeared on arXiv, the open access database of the Cornell University, which explained the structure of new revolutions, with a data-driven approach, by analysing the network of concepts on Wikipedia, the largest open encyclopedia in the world. What emerged is that new concept networks build not only on previous knowledge core but on filling knowledge gaps. Scientific discoveries, generally awarded by Nobel prizes, rely on *identifying uncharted gaps*, as well as (obviously) advancing field-specific solutions (Ju et al., 2020).

On top of the debate about interdisciplinarity in research, recent scientific literature also highlighted the fundamental role of transdisciplinary collaborations among the academy, the industries and the citizenship (Lang et al., 2012) to stimulate a successful ecological and *sustainability transition* (Markard et al., 2012). According to Lang et al. transdisciplinarity requires to develop solution-oriented knowledge through a mutual learning processes starting from societally relevant problems and it is defined as a *"reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge"*. In this sense, interdisciplinarity and transdisciplinarity are nowadays fundamental to lead a socio-technical transition towards a sustainable management of our society and of our Planet. Generally speaking, according to Markard et al. a transition (technological, institutional, organizational, or socio-cultural) points to distant scenarios and should involve very different actors from the academia, institutions or directly the citizens themselves for a very long period (generally more than fifty years).

The current environmental challenge we are facing, from the climate change to the necessary ecological transition, is probably one of the biggest and most urgent challenges humanity has ever been called to face. Thus, how can a single PhD thesis be up to such a huge challenge? In the *"Nature"* special issue, publicly released only two years before I applied for the PhD position, it was pretty clear the call for PhD, postdoc, scientists and researchers in general, to move from highly specialized and applied researches - which, in many cases (honestly speaking) the industry is able to develop for itself - to the *grand challenges* and interdisciplinary questioning. Again another doubt. Could it be possible to do an interdisciplinary PhD? The *"Innovation for the Circular Economy"* PhD programme I started three years ago was promising. General interest about Circular Economy was rising among the society, universities and industry in an incredible and fast way, as it was - and it is - promoted as the new economic paradigm to *regenerate* and *restore* our sick Planet, to boost green and sustainable investments for enterprises, as well as introducing new lifestyles for a sustainable development. When I started my PhD, these premises were great, and, obviously, fascinated me since in my academic career I always attempted to move from one field to another one.

This text has not to be read as a technical academic work. Since the challenge was so wide, I explored different tools and approaches (starting from the most up to date literature review on Circular Economy[1]), from the use of life cycle assessment and the input-output tables up to the novel circularity indicators that were emerging exactly during the PhD. The result, initially, was a complete chaos. There are no tools that, apparently, can be applied to different levels, every academic field appears to be closed in itself without communicating with the other ones, or collaborating only for pilot researches. Every field generally speaks its own language. Economists target economists, designers only designers, philosophers only philosophers. Thus, I tried to understand the different points of view related to the circular economy, not without difficulties, from philosophical inquiry to the design of products. Along this path I realized I would not be able, in such a short time, to technically join several, dozens, of methodologies. Thus, the outcome has been the development of a general theoretical framework, based on *Information System Design Theory*, to put the foundations of future researches in the field of circular economy. During my exploration I shifted to a more philosophical approach as one of my first research questions - *Is the circular economy a new paradigm or just a relabelling of old knowledge?* - was properly related to the new paradigm

[1] See for instance Corona et al. (2019), Kristensen et al. (2020), Parchomenko et al. (2019), and Sassanelli et al. (2019)

and because of deepening environmental ethics, it was not possible to try to assess the environmental impact of any product without having in mind a precise definition of what is *right* and *just*, and what is not. About philosophy and environmental challenges I wish to share this brief extract, which perfectly fits in this work (O'Brien et al., 2015):

> *"Philosophy and normative theory may provide conceptual tools and methodologies for assessing environmental challenges. When philosophers or theorists consider an issue, they strive to go beyond the most obvious level of inquiry. Philosophers look for causes in an effort to understand the underlying nature of things. In this sense philosophy is a quest for knowledge. This pursuit depends not so much on information gathered through research as it does on speculation about a given question. Philosophy is sometimes referred to as the most general science, in that its project is to discover underlying truths. All science seeks to find answers. In this manner, philosophy can be viewed as both the pursuit of wisdom and the knowledge itself that is gained through philosophical inquiry.*

In this work, I tried to set the basis, in my opinion, of how to define a *Circular Thing*, i.e. an object that can last forever and that can allow the Earth, not only the humanity, to live in the so-called *safe and just space* (Raworth, 2017). What does it mean? Can an object last forever? Obviously, no. Every object can be repaired or reused, renovated or remanufactured, materials can be recycled. That is obvious. But recycling a material, or reusing a cup for instance, is it more environmentally friendly or better than producing a new object? Continuing, what does it mean environmentally better? With comparative life cycle analysis, for instance, it can only be affirmed that one object has less impact, or better saying produce less externalities, than another one. Does this imply that we can reuse a cup thousands of times for each person (currently more than seven billions) in the world still remaining within the planetary boundaries[2]? Does environmentally better mean that an object is regenerative, i.e. it improves the environment and the local ecosystem? Basically, no. As environmental economics teach us, every process has an impact - in terms of emissions, water or land use, and so on - thus, a reference system is necessary. The reference should be the regeneration rate of a renewable resource or the assimilative capacity of the ecosystem/planet (when speaking about emissions of substances into the biogeochemical cycles for instance). Finally, how can a *Circular Thing* be defined? Roughly speaking, it should be an object that can be produced (reused, repaired, or even reproduced) indefinetely in time (for hundreds of years, at least) and in space (for every person in the world). Obviously, not all objects should be produced for everyone, but only the basic human needs (housing, energy, food, ...). If we are able to evaluate the impacts necessary to produce the basic human needs, then, theoretically, we should be able to evaluate the remainder of CO_2 emissions, just to give an example, we have to produce every other good/commodity. The first step to do such a giant work is to define the *units*, *boundaries*, *laws of interactions* and

[2]The nine planetary boundaries as defined by Rockström, W. Steffen, et al. (2009) are: climate change, ozone layer depletion, air pollution, biodiversity loss, land conversion, freshwater withdrawals, nitrogen & phosphorous loading, chemical pollution, and ocean acidification

the *system states*, as the information system design theory tells us. Regarding goods and commodities the starting point is the design of the object, as well as the material composing it, which are the fundamental units to assess the environmental impacts (the materials) and the potential of recovering (the design criteria). Regarding the rules, Ostrom (1990) gave us the way to define an enduring common-pool resource, which in my opinion should not be the raw material itself (also because recent studies largely agree that we are not running out of materials, neither of energy[3]) but the object itself. According to Ostrom, for a long-enduring common-pool resource several principles are necessary. The most important one, in my opinion, is the perfect communication among every appropriator and that the appropriators themselves have to define the rules. A few months ago, thankfully, the European Union started to go in this direction by declaring the *right to repair* (EP, 2020a; EP, 2020b), thus, certain firms (unfortunately not all) will have to release the scheme, the layout of certain products (e.g. washing machines, dishwashers, fridge, TVs, ...) allowing to repair them easily. In this sense, I named *Circular Commons*, the future common-pool resources (i.e. the goods themselves) and their governance. The environmental challenge is more urgent than ever, thus we cannot wait for perfect and without error assessment. We need to enter in a *Post-Positivist Natural Science* school of thought.

In conclusion, this is an interdisciplinary work, full of examples developed during my Ph.D., which can support (I hope) everyone who is struggling with the circular economy and is working for a sustainable future.

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[3]See for instance Hemmingsen (2010), Jowitt et al. (2020), McAfee (2019), and Priest (2012)

Summary

A transition towards a circular economy is nowadays more necessary than ever to face with the current environmental crisis. However, circularity and closing the loop strategies do not necessarily mean and imply either a better environmental performance or to balance the human pressure to Nature with the assimilative and regenerative capacity of the Planet. For this purpose, the state of the art related to environmental and circularity assessment has been discussed in detail througout the whole thesis.

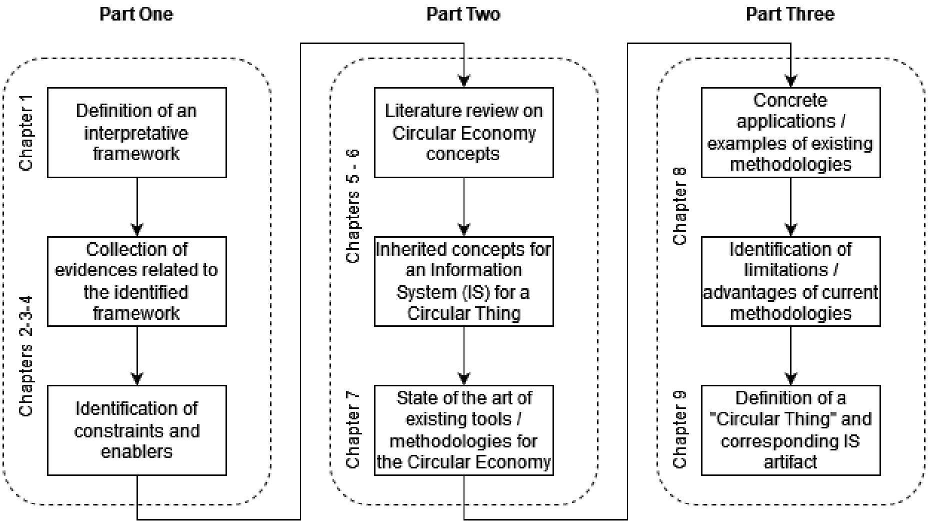

Figure 1: Overview of thesis structure

The whole thesis is subdivided in three parts. An overall structure of the work is shown in Figure 1. In brief, in part I a general framework - energy-materials-information - is proposed starting from a historical overview and the most relevant up-to-date scientific literature (chapters 1 to 4). The thought of fundamental thinkers in environmental economics and sociology and in the definition of the planetary boundaries such as, among others, Kenneth Boulding, Herman Daly, Denis and Donella Meadows, Paul Ehrlich, Howard Odum, Johan Rockström, as well as in the management of Commons and the social dilemma (Jeremy Rifkin, Elinor Ostrom, Garrett Hardin, Carol Rose) and in the materials and waste management (Thomas Graedel, Walter Stahel, David Pearce and Kerry Turner), are reported and analyzed in order to provide a general context and a robust interpretation of the ongoing circular and ecological transition. In part II the main underlying concepts (chapter 5), schools of thought (chapter 6) and methodologies (chapter 7) related to the circular economy are explained and discussed. Finally, in part III three applications are presented highlighting both limitations and opportunities (chapter 8) in order to introduce in the final chapter an Information System Theory for the Circular Economy (chapter 9).

Each part/chapter is dedicated to answer one, or more, research question/subquestion, creating a unique narrative aimed at defining, in the last chapter, a *circular thing* addressing two main questions: How a circular thing is defined? What are the main features to define a circular object? Table 1 summarizes the main questions addressed in each chapter.

Table 1: Research questions addressed by each chapter

Chapter	**Research question**
1. House on fire	Which is a proper framework for the Circular Economy transition that can include physical constraints and enablers for the transition?
2. Energy	What are the main aspects (e.g. constraints/enablers) related to energy?
3. Materials	What are the main aspects (e.g. constraints/enablers) related to materials?
4. Information	What are the main aspects (e.g. constraints/enablers) related to Information?
5. An emerging paradigm 6. The circular economy	What are the main inherited concepts for circular economy?
7. How to assess circularity	What are the main existing tools and methodologies to assess the circularity and the environmental impacts?
8. Applications	Do existing methodologies allow to assess the circularity in a holistic way taking into account micro, meso and macro aspects of a system?
9. Circular Thinking	How a circular thing is defined? What are the main features to define a circular object?

First, in Part I, starting from the earlier environmentalist debates about the Limit to Growth (D. H. Meadows, D. Meadows, et al., 1972) and the boundaries of the Planet (Boulding, 1966; Daly, 1974; H. T. Odum, 1996) and following the discussion set up by Rifkin (2015) regarding the industrial revolutions, a quite broad and general interpretative framework to be adopted - i.e. the energy, material, information framework - has been introduced in chapter 1. Then, in chapters 2 and 3 the current knowledge related to global energy and material production, as well as the consumption, has been discussed to point out the main constraints and physical limits to be taken into account. What emerged from these two chapters is that the urgency on reducing energy and material consumption is not as urgent as typically depicted. Indeed, the increase of energy consumption may be entirely satisfied by renewable energy production (Armaroli et al., 2017), although the energy transition will still need a few decades to achieve such a result (IEA, 2021). Thus, one of the emerging issue for new renewable energy technologies is related to the necessary raw materials, e.g. metals and rare earths, and the so-called embodied energy and carbon needed to produce, transport and dispose such materials. Consequently, the knowledge about global material production and consumption has been summarized in chapter 3. According to the relevant literature, a counter-intuitively viewpoint emerged. The lack of raw materials in Nature is not completely true (Jowitt et al., 2020). Although satisfying the human needs for thousands of years necessarily needs to perfectly close the material loops, this is not true in the very-near future (decades, or even hundreds of years), as the rhetoric about the circular economy is highlighting and exploiting as rationale to induce a quick transition. On the contrary, the real emergence related to materials' exploitation is twofold. On one side, the uneven distribution of materials on the Planet and the difficulty to find substitute materials, especially for high tech and energy technologies, may cause geo-political risks (see rare earths debate related to the Chinese production). On the other side, the environmental issue is due to the environmental impacts, in terms of carbon dioxide emissions or other pollutants, the life cycle of the materials - from extraction and production up to the disposal of the materials - generates. In other words, humanity will not be affected by a lack of resources (at least in the near future) but, for instance, by global warming due to the CO_2 emissions. These considerations bring to the development of criticality material indices and to put a global effort within the circular economy framework, to face the use of materials in general (Thomas E Graedel, Barr, et al., 2012). Finally, to facilitate a circular transition, open, transparent, and complete *information* are necessary as discussed in chapter 4. Information, in its broadest and most general meaning, is necessary to monitor and control the global consumption and production, to stimulate proper behaviour in consumers and firms and to, as defined by Ostrom (1990), manage a long-enduring common-pool resource (CPR), or as I defined a *Circular Commons*. The groundbreaking work of Ostrom (1990) brought us to identify one of the basic concepts of environmental economics and human ecology, i.e. the balance between the extraction rate of a resource and its regeneration rate. To evaluate it, as human ecology highlights since more than one hundred year, every consideration related to the use of materials or energy consumption should be necessarily scaled at the global scale. This consideration is in line with the so-called planetary boundaries defined by Rockström, W. L. Steffen, et al. (2009), just one decade ago, and with the idea to live within the *safe and just space* (Raworth, 2017).

Second, in Part II, on top of the energy-material-information framework, in chapters 5 and 6, the concepts and schools of thought underlying the Circular Economy have been explored by identifying the main features each previous knowledge may provide to the novel circular economy. By exploring the question *"is Circular Economy a new paradigm or just a relabelling of old knowledge?"*, previous concepts, as the sustainable development definition (Brundtland et al., 1987), the environmental economics (Pearce et al., 1990), the biomimicry (Benyus, 1997) schools of thought, as well as the cradle-to-cradle (McDonough et al., 2010), industrial ecology (T. Graedel and Allenby, 2010), or the regenerative design (Lyle, 1996) ones, have been analyzed in detail. What emerged is that the circular economy may act as an umbrella for previous concepts and knowledge. For instance, from cradle-to-cradle and industrial ecology, the CE may inherit the systemic perspective, the closing-the-loop strategies, and the differences between the biological and technical cycles, while from biomimicry a deeper philosophical insight related to the concept of the Nature itself, i.e. *Nature as a model, as a measure, and as a mentor* (Benyus, 1997). From the sustainable development definition (Brundtland et al., 1987), the idea of time is the fundamental concept to take into account, i.e. to do not exploit future generation needs, while from the regenerative design school of thought the concept to have a reference system, i.e. the current state, from which any assessment has to start from. Finally, from physical sciences and environmental economics the planetary boundaries (Rockström, W. L. Steffen, et al., 2009), starting from the studies related to the bio-geochemical cycles, provide the fundamental and elementary interaction laws with Nature.

Third, in chapters 7 (part II) and 8 (part III) the most common methodologies to assess the circularity of products or processes, inherited from environmental assessment methodologies, are introduced. In particular in chapter 7 the Life Cycle Assessment approach, the main Design criteria (from eco-design to the Design for Disassembly) and the elementary properties of products, as well as the system dynamics functioning have been explained. In order to design a Theory, as illustrated by the Information System Design Theory (Gregor et al., 2007), the assessment methodologies and tools are fundamental in order to implement and instantiate an IS and validate it. On the other side, the system dynamics is necessary to study the law of interactions, while the products' properties are necessary to define the purpose and scope, as well as the constructs of an IS. In particular, in chapter 8, three subquestions have been addressed while exploring three different tools and methodologies (a Life Cycle Assessment comparative study between reusable and single-use cups, a Circularity indicators for the built environment, and an dynamic input-output model to evaluate Covid-19 restrictions impacts in Italy) to assess the circularity: 1) *Which is the environmental break-even point for reusable cups with respect to single-use cups?*; 2) *How to improve the environmental assessment of the raw materials used in a Building Circularity Indicator? How to quantify the End of Life potential of materials and building components worth recovering by adopting Design for Disassembly (DfD) criteria?;* and 3) *What are the impacts generated by the Covid-19 restrictions in terms of economic losses and GHG emissions on Italian national economy?* Finally, in chapter 9, a general process, a design method, based on the ISDT to define a *Circular Thing* is discussed. In this work, the design process is based on the model of Gregor et al. (2007) in order to conceptualize an IS artifact. In particular, the IS corresponding to a *Circular Thing* is defined. The six main components[4] necessary for an Information System artifact has been described. These features ended in a quite broad definition of a *Circular Thing*, i.e. *A Circular Thing exists if and only if it is defined together with every other Thing (Artificial Thing set) and has to indefinitely-last (the object itself or its future transformation) providing its functionalities to every people who needs them lying within the local or planetary boundaries.*

Concluding, throughout the whole thesis some applications from original studies conducted during my PhD are reported to, first, enrich the discussion with examples/case studies (chapters 5 and 6) and, second, to discuss the main limitations of current assessment methodology (chapter 8). More precisely, the following author's contributions can be found:

- *Easy Open Data* (Dario Cottafava, 2018), a work that introduces the basic concepts related to the Sustainable Development Goals (SDGs) (chap. 1), to the Open Data movement (chap. 4) and to the posthuman philosophy (chap. 5);
- "Big Data, social networks, and well-being" (Dario Cottafava, 2020), a book contribution published in the book *Regenerative design in digital pracice. A handbook for the built environment* (Naboni and Havinga, 2020) that presents a brief overview on the regenerative design school of thought providing three examples/applications for the built environment linking concepts as crowdsourcing, well-being and adaptive comfort (chap. 5);
- "From flow to stock. New Circular Business Models for integrated systems: a

[4] 1) Purpose and scope, 2) Constructs, 3) Principles of form and fuctions, 4) Artifact mutability, 5) Testable propositions, 6) Justificatory knowledge

case study on reusable plastic cups" (Dario Cottafava, Riccardo, et al., 2019), an inproceeding presented at the *"23rd International Trade Fair of Material & Energy Recovery and Sustainable Development, ECOMONDO"* that describes a novel circular business model for reusable cups based on a pilot project run in the City of Turin in 2019 (chap. 5);

- "Circular economy: new paradigm or just relabelling? A quantitative text and social network analysis on Wikipedia webpages" (Dario Cottafava, Ascione, and Allori, 2019), an inproceeding presented at the *R&D Management Conference 2019* held the 17th–21st June 2019 in Paris (France) that, starting from the question *Is the circular economy a new paradigm or just a relabelling of old knowledge?*, investigates the interconnections and relationships among the Circular Economy and other related concepts by analysing the Wikipedia network of pages (chap. 6);
- *Benchmarking on circularity and its potentials on the demo sites* (Dario Cottafava, Ritzen, and Oorschot, 2020), a technical report developed at the early stage of the Drive0 EU research project that provides a detailed summary of the main concepts related to the Circularity Indicators and other environmental assessment methodologies for the built environment (chapters 7 and 8);
- "Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects" (Dario Cottafava and Ritzen, 2021), an original paper that introduces a novel circularity indicator for the built environment by linking embodied impacts and design for disassembly criteria with the material circularity indicator of the Ellen MacArthur Foundation (chapters 7 and 8);
- "Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups" (Dario Cottafava, Costamagna, et al., 2021), a comparative Life Cycle Assessment between single-use and reusable cups that describes a novel methodology to calculate the environmental break-even point based on the pilot project described in Dario Cottafava, Riccardo, et al. (2019) and run in the City of Turin (chapters 7 and 8)
- "COVID-19 impact on the Italian economy: past, present and future scenarios" (Dario Cottafava, Gastaldo, et al., 2021), a work to show the functioning of the Input-Output tables and their pros and cons for environmental/circularity assessment which studies the economic and environmental impact of the COVID-19 restrictions on the Italian economy during 2020 by analysing the evolution and the dynamics of the national economy considering the interconnections among the economic sectors (chapters 7 and 8);
- "Sustainable Development Goals research in Higher Education Institutions: an interdisciplinarity assessment through the design and testing of an entropy-based indicator" (Dario Cottafava, Ascione, Corazza, et al., 2021), a research about an Information System design method related to an interdisciplinarity sustainability index to assess the interdisciplinarity of the SDG-related research contributions in Higher Education Institutions - used as an example to provide insights on how to define an Information System design method for the Circular Economy (chap. 9).

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Part One. Introduction

1. House on fire

With the new millenium, we have entered into a new geological epoch. *Welcome to the anthropocene* (Slaughter, 2012). The Holocene, the last epoch in geology, is definitely ended. Anthropocene, term coined by the biologist Eugene Stoermer and later publicly spread by the atmospheric chemist Paul Krutzen, nobel-prize winner, derives from Greek (anthropos, human, and kainos, new or recent) and it refers to a new geological epoch in which the human activities are deeply changing the chemical, physical and biological properties of the Earth. From the beginning of the Holocene, around 10,000 years ago, the humanity has never had such a deep impact on the atmo, bio, geo, and hydrosphere as in the last two hundred years. From the first industrial revolution, the fossil fuels entered our society and economy, and from 1776, year of the James Watt's steam-engine invention, they completely modified our world. This sharp and sudden veer in the human-nature relationship, if thought in a larger scale (Figure 1.1) of thousands of years, is just a Dirac delta, to say it in mathematical terms. Nothing more than an error, a signal noise in the Earth life.

Although not yet officially recognized as a geological epoch by the International Commission on Stratigraphy (ICS), the largest scientific organisation within the International Union of Geological Sciences (IUGS) - *officially we still live within the Holocene Epoch* - the word Anthropocene reached the public opinion globally, engaging all types of research fields. The ICS itself founded a research working group, with dozens of scientific contributions, on the Anthropocene (ICS, 2020). Writers, film directors, philosophers, and artists also started to discuss about the anthropocene, but

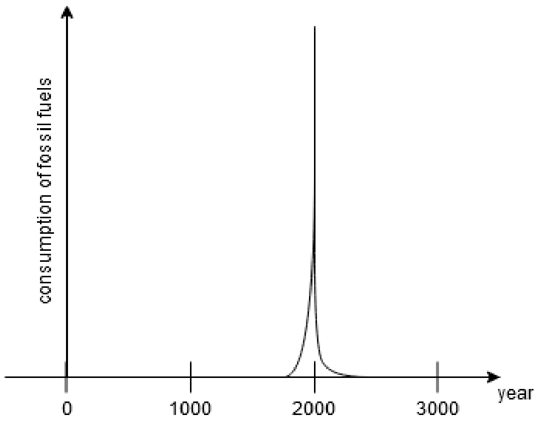


Figure 1.1: Fossil fuels consumption in human scale. Adapted from Rovers (2019, p.190)

from a different point of view (Orusa, 2020). Despite the great popularity of the term, an open debate is ongoing about the word anthropocene itself, if it is the right word. For instance, Haraway (2015) questioned if more proper terminologies may be used. Indeed, anthropocene reminds to the term anthropos (human) but is it proper to attribute the geological change to the human species? Haraway (2015), for this reason, proposed to adopt *capitalocene*, term deeply analyzed in the book "Anthropocene or capitalocene?: Nature, history, and the crisis of capitalism" (Moore, 2016), in order to focus on the capitalism as a way of organizing *Nature as a whole* and not only to the human species as the word anthropocene suggests.

Despite the debate on when, and if, the Anthropocene has begun, the story of the nature exploitation started a long time ago. As already mentioned, the high dependence from fossil fuels of human activities started at the beginning of the XIX century, around two hundred years ago. On the contrary, contemporary environmentalism only started and emerged in the second half of the XX century. Precursory studies, such as the *The Limits to growth* of D. H. Meadows, D. Meadows, et al. (2018), created a sense of urgency about environmental exploitation. They simulated the possible consequences for humanity and the Earth itself if no strict policies would be adopted, pointing out the necessity to immediately reduce the human pressure on the environment and the exploitation of the raw resources. At the same time, Boulding (1966) and other academics, in more general terms, moved the academic and public discussion on the planet boundaries, inviting to think the Earth as a closed system, and they put the basis for the environmental economics, undermining the myth of the eternal economic growth for the very first time. In the same years, the senator Robert Kennedy of the United States of America highly criticized the Gross Domestic Product (GDP) as a way to measure the wealth of a Nation and the addiction to always follow the economic growth. In a famous speech the senator stated on March 18th 1968 (Wahl, 2016, p.224):

Our Gross National Product, now, is over $800 billion dollars a year, but that Gross National Product - if we judge the United States of America by that - counts air pollution and cigarette advertising, and ambulances to clear our highways of carnage. It counts special locks for our doors and the jails for the people who break them. It counts the destruction of the redwood and the loss of our natural wonder in chaotic sprawl. It counts napalm and counts nuclear warheads and armored cars for the police to fight the riots in our cities. It counts Whitman's rifle and Speck's knife, and the television programs which glorify violence in order to sell toys to our children.

Yet the gross national product does not allow for the health of our children, the quality of their education or the joy of their play. It does not include the beauty of our poetry or the strength of our marriages, the intelligence of our public debate or the integrity of our public officials. It measures neither our wit nor our courage, neither our wisdom nor our learning, neither our compassion nor our devotion to our country, it measures everything in short, except that which makes life worthwhile. And it can tell us everything about America except why we are proud that we are Americans.

Capitalism is in crisis (Moore, 2016; Rifkin, 2015). Several decades of debates and criticisms proved all the limits of the current economic system and of our dominant behaviour over the nature. Humans, we, are only a small part of it (Braidotti, 2013); a unique gear, a single mechanism in a huge machine that, actually, is not working properly, is almost broken. With the words of Pliny the Elder, *the power and majesty of nature in all its aspects is lost on one who contemplates it merely in the detail of its parts and not as a whole* (Wahl, 2016, p.73). Especially, in the past two centuries, our blame has been to be arrogant and proud. *Nature* has been assumed as a source to *extract* resources, and not as a partner, as a source of learning, as a *model* to be imitated (Benyus, 1997). For this purpose, first, in this introductory chapter the history of the past industrial revolutions, and the birth of the contemporary environmentalism, will be briefly discussed in order to understand where the environmental crisis emerged, what are the main limits of the current "management" system, and what tools and instruments might be used to face the ecological transition. In section 1.1, the limits to the growth model is discussed, as treated originally by D. H. Meadows, D. Meadows, et al. (2018) in the Seventies, while in section 1.2 a brief description of the past industrial revolutions is provided, in order to give the preliminary insights, for section 1.3, to imagine the correct framework to analyze the current transition.

1.1 The limits to growth

Not blind opposition to growth,
but opposition to blind growth.

Sierra Club
(D. H. Meadows, D. Meadows, et al., 2018, p. 154)

The Limits to growth, written by D. H. Meadows, D. Meadows, et al. in the seventies, was probably one of the most visionary studies of the past century where, for the first time, the planetary boundaries were taken into account in a holistic analysis about the evolution and development of the humankind. Donella Meadows, Dennis Meadows, Jorgen Randers and William Behrens, together with many other researchers and academics of the System Dynamics Group of the Massachusetts Institute of Technology (MIT) in 1972 published a report on the *predicament of mankind* for the Club of Rome envisioning the society will achieve the planetary limit capacity before 2100 if no interventionist policy would be adopted to reduce and control the industrialization growth, the pollution production, the raw material exploitation or the constant population growth. The aim of the report was not to exactly predict the evolution of the population growth or of the future pollution level, but rather to envision, with the use of the system dynamics (D. H. Meadows, 2008), the possible path for the following century for the humankind and its relationships with the natural ecosystem. System dynamics (SD) is a methodological tool to look and investigate the functioning, the dynamics of a system through the analysis of stocks and flows with the lens and the focus on their causal relationships and the effect of feedback loops. In the case of natural ecosystem, for instance, the difference between stocks and flows may be explained in terms of future availability. Resource, or energy, flows are the ones whose present use does not affect future availability (e.g. if a solar panel uses solar radiation to produce energy today, it does not affect the availability of the solar radiation of tomorrow). On the contrary, resource stock use will influence the future stock (Perman et al., 2003, p.18). A further distinction for stock regards whether a stock is renewable or not-renewable. For instance, a forest, or any other biotic stock, is a renewable stock, while petrol is not, although, theoretically it is a renewable one. The term not-renewable, thus, is a feature of the stock depending on the reproduction rate, i.e. how the stock regenerates itself. In the case of fossil fuel, the reproduction rate lies in a completely different time scale and, consequently, for the human purpose it can be considered as a not-renewable stock.

In general terms, with the word of D. H. Meadows, *"a system is an interconnected set of elements that is coherently organized in a way that achieves something ... (it) must consist of three kinds of things: elements, interconnections, and a function or purpose"*. Thus, the elements of a system are interconnected through causal relationships which lead the dynamics of the system to achieve its purpose. *Coherently organized* means that the purpose of the system is the fundamental rule which creates emergent behaviour and allows to consider a system as *"more than the sum of its parts"* (D. H. Meadows, 2008, p.11). In *The Limits to growth*, authors' purpose was to analyze the world system by considering the most influencing agents of change to stress and test the capacity of the Earth. In their model, the five fundamental factors influencing the world dynamics - population, capital, food, not-renewable resources, pollution - were interrelated through mutual influences and it was not possible to study any of such factors without considering them, all at the same time (D. H. Meadows, D. Meadows, et al., 2018, p.106). To envision the world dynamics, the concept of exponential growth is of fundamental and central importance. Indeed, the feedback loops within a system regulate its rate of growth, or decay, through their *reinforcing* or *balancing* effect. A feedback loop is a closed path of

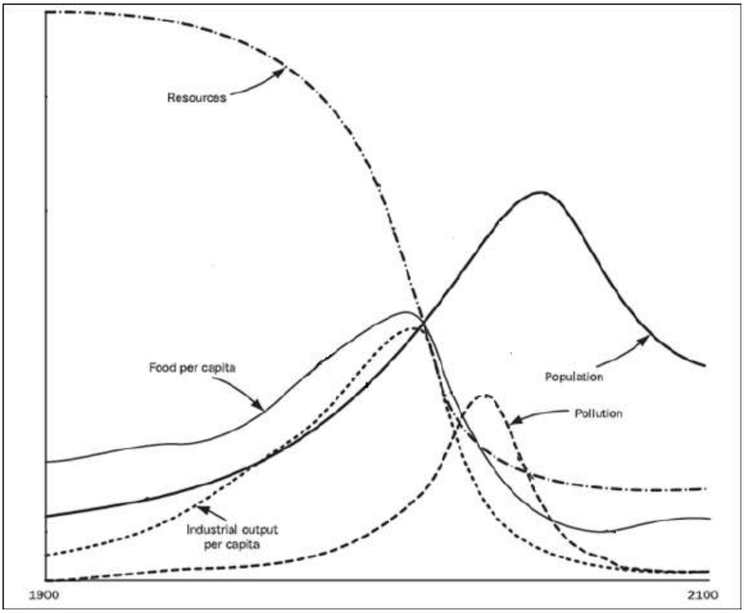


Figure 1.2: Representation of the limit to growth simulation. Dynamic of the five most relevant factors - population, pollution, industrialization, food production and resources - in the world model of *The Limits to growth*. Source: D. H. Meadows, D. Meadows, et al. (1972)

causalities which allows a stock to reinforce, or balance, its growth. For instance, the population can be modeled through two basic feedback loops - one reinforcing and one balancing - which define its growth rate. In other words, a larger population increases the birth rate (reinforcing loop) - i.e. more people, more births, more people - and the death rate (balancing loop) - more people, more deaths, less people. D. H. Meadows, D. Meadows, et al. (2018) analyzed the effects of multiple loops in their model, and the relative exponential growth of the five considered factors, predicting that such rate of growth (tuned on data related to previous decades) was not sustainable at all. They compared several scenarios with the Business as Usual (BaU) scenario and in each case a sudden collapse of the human population due to the world capacity would happen before 2100 (Figure 1.2). Each scenario simulated the effect of a growth control policy - e.g. birth control, pollution reduction - and highlighted the evolution of all other relevant factors. In all the cases, the control policies were not sufficient to prevent the sudden collapse of the human population due to a lack of resources, land for food production, or due to a too high a level of pollution. (D. H. Meadows, D. Meadows, et al., 2018, chap. V). In order to avoid such a catastrophic scenario, the authors suggested that the only reasonable path to lie within the planet boundaries should be a precise control and limitation in all relevant analyzed factors by linking, for instance, dynamically the birth rate with the death rate to perfectly balance the two contributions (D. H. Meadows, D.

Meadows, et al., 2018, chap. VI) and to put the world system into a global equilibrium. According to the authors, such a perfectly controlled scenario is not realistic but many policies may affect the scenario in such a direction; for instance, they anticipated many current policies and technologies related to the circular economy and, more in general, to the sustainable development: i) new methods to reduce the impact of waste disposal and to recycle materials, ii) new material treatments to increase extraction efficiency and reduce material exploitation, iii) re-design of the commercial products to enlarge their useful lifetime and to facilitate repairs and fixings of components, iv) reduction and control of toxic materials of components within products, v) use of renewable energies, e.g. solar radiation, and so on. Recently, the approach and the conclusions of D. H. Meadows, D. Meadows, et al. (2018) has been largely criticized. Indeed, as discussed recently by McAfee (2019) in his book *More from less: The surprising story of how we learned to prosper using fewer resources—and what happens next*, the authors did not take into account various fundamental aspects such as technological improvement or the discovery and consequently the availability of new resources stocks which can act as balancing feedback loops. Despite the critics, *The Limits to growth* is still considered one of the starting point of the environmental studies that already in the Sixties and in the Seventies put the seeds of the current circular economy paradigm.

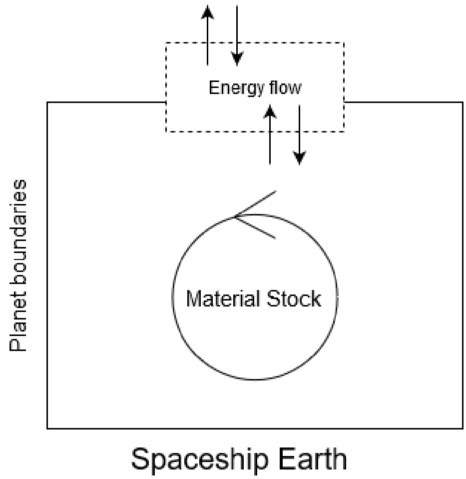


Figure 1.3: Simplified representation of the Spaceship Earth boundaries. The Earth is a closed system. Energy flow can be exchanged, while materials are limited within the world boundaries.

The same strategy for a global equilibrium was also envisioned by Daly (1974) who stated *"a steady-state economy is defined by constant stocks of physical wealth (artifacts) and a constant population, each maintained at some chosen, desirable level by a low rate of throughput – i.e., by low birth rates equal to low death rates and by low physical production rates equal to low physical depreciation rates, so that longevity of people and durability of physical stocks are high"*. Similarly, Boulding (1966), one of the father of environmental economics, in his article "The economics of the coming Spaceship Earth" discussed that *"a change in orientation that is required if mankind is to achieve a perpetually sustainable economy"*, pointing out the need of economic measures in terms of flows of materials. The term *Spaceship Earth*, clearly influenced by the space discoveries of the sixties, refers to the resource limits of the Earth. Indeed, considering the whole Earth as a single spaceship, a precise management of the available resources is necessary. The spaceship Earth is a closed system where there is a limited amount of material stock and the solar radiation is the only entering flow from outside, as depicted in Figure 1.3. Thus, if mankind has to last forever, an infinite ecological cycle should be maintained where materials usage is balanced by the recycled materials, and energy usage cannot exceed the entering flow from the sun (Boulding, 1966).

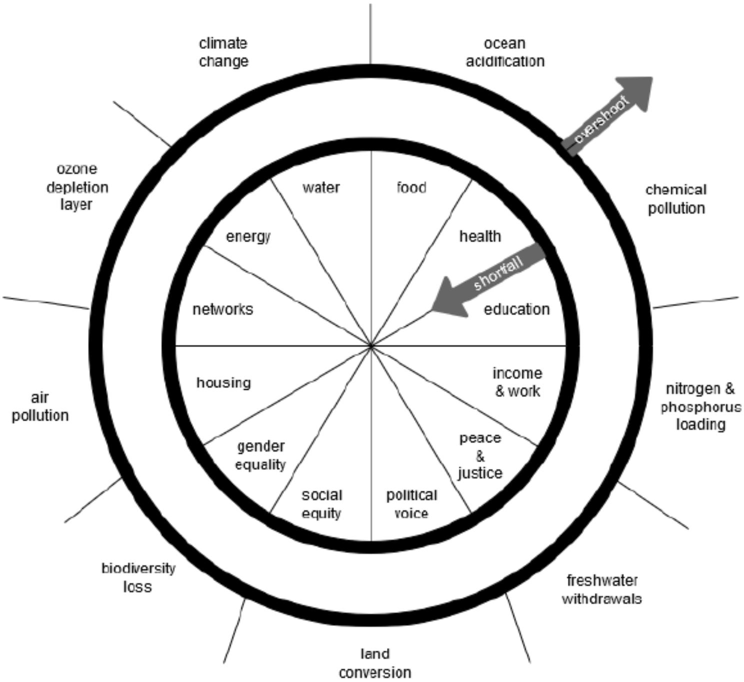


Figure 1.4: Representation of the *safe and just space for humanity*. Adapted from: Raworth (2017)

More recently, Raworth (2017), economist of the universities of Oxford and Cambridge, in her book *Doughnut Economics: seven ways to think like a 21st century economist* proposed a new framework to measure the development of the society within the planetary boundaries. The introduced doughnut representation (Figure 1.4) takes into account at the same time both environmental boundaries and the minimum welfare for the society necessary for a *safe space*. In a unique framework, Raworth included the overshoot of the main nine planetary boundaries[1] and the shortfall of social foundation[2] by defining the so-called *"safe and just space for humanity"*. Raworth identified the unique space for a sustainable development (Brundtland et al., 1987) for the humankind and represented it properly by a doughnut between the ecological ceiling and the minimum level of welfare, i.e. the social foundation. Thus, the only way to lie within these two limits is the correct balance between social needs and planetary limits by designing a *"regenerative and distributive economy"* (Raworth, 2017, p.23-25).

1.2 A flashback on industrial revolutions

Understanding the present day and the current situation of our world needs an appreciation of the past. Facing the current ecological crisis, with awareness, needs to know precisely what in the past centuries worked and what brought us in the current crisis. To do so, a quick jump in the industrial revolutions, a brief overview of the past two hundred years could improve our knowledge of the mechanism that moved our society on the wrong lane, on the dangerous and risky path in which we are lying nowadays. To this purpose, Rifkin (2015), in his book *The zero marginal cost society*, analyzed the first two industrial revolutions to better frame and explain the ongoing third industrial revolution. According to Rifkin (2015) each previous "revolution" was generated by new emerging technologies related to the generation of energy, to the transportation of products or materials, and to innovative ways to communicate among people. Thus, each past societal and economic change was provoked and caused by a new *"communication / energy / transportation matrix"*, i.e. simultaneous innovation for communication, energy and transportation able to activate cascade and fast positive technological improvement in all the three aspects, as defined by Rifkin (2015, p.30).

The feudal economy, within the framework introduced by Rifkin, was described as a subsistence communication / energy economy. Also the prototype of the subsequent industrial revolution, i.e. the transition from the feudal to the market economy, may be framed with the Rifkin's matrix. Indeed, originally within the feudal economy, almost all production was for local and immediate use and only very few products (e.g. spices, or rare and precious metals) were exchanged among geographically far away territories. At the end of the Middle Ages, the transition was boosted, first, by the emergence of the windmills - the first one was built in England in 1185 - in Northern Europe and by the large diffusion of watermills, and, secondly, by the invention of the printing press, by Johannes Gutenberg in 1436. These two technological inventions, together with the increasing sea transport, thus, provoked the overcoming of the subsistence feudal economy (Rifkin, 2015, p.39-42).

Similarly, the first (1760-1840) and the second (1870-1914) industrial revolutions may be interpreted with the communication / energy / transportation matrix. According to Rifkin, the first one was characterized by the well-known steam engine, invented by James Watt in 1776, which suddenly revolutionized the textile manufacturers, as well

[1] Planetary boundaries: climate change, ozone layer depletion, air pollution, biodiversity loss, land conversion, freshwater withdrawals, nitrogen & phosphorous loading, chemical pollution, and ocean acidification

[2] Social Foundation: health, food, water, energy, networks, housing, gender equality, social equity, political voice, peace & justice, income & work, education

as the transport system with the rapid spread of railroads and steam-powered trains. Meanwhile, the first steam-powered printing presses started to produce newspapers at a very high speed and low price, and the invention of the telegraph considerably improved the communication and information systems. Similarly, the second industrial revolution was caused by the simultaneous discoveries and diffusion of oil & electricity, the telephone, and the combustion engine, which allows the spread of cars and trucks (Rifkin, 2015, p.50-67). The discovery of oil spread all around the world in a few decades: in 1868 the Standard Oil Company was founded by John D. Rockfeller, and, in 1911, thanks to the *Sherman Antitrust Act*, the Supreme Court of the United States of America (USA) ordered the separation of the company, due to its monopolistic position in the USA. Meanwhile, Alexander Graham Bell, in 1876, patented the telephone (at the same time of the italian Antonio Meucci) and in 1885, he created the American Telephone and Telegraph (AT&T) company. Again in a few decades, due to its rapid diffusion, AT&T reached a monopoly: in 1918, the telecommunications industry was nationalized for national security, and, in 1921, the Senate Commerce Committee stated *"telephoning is a natural monopoly"* (Rifkin, 2015, pages 59–60). At the same time, the spread of oil and the combustion engine, and of the electricity completely changed the development of the cities. Indeed, thanks to the diffusion of cars and trucks, the logistics poles gradually moved from being closed to the train stations to big logistics centers in the suburbs of the cities.

Finally, Rifkin continues, the ongoing *third industrial revolution* may be connected to the introduction and spread of the rapid adoption of the newest renewable energy technologies, the creation of Internet (which stimulates a wide range of new technologies), and the still emerging 3D printing technology, and other democratic manufacturing processes. The running industrial revolution, although in some aspects can be interpreted with similar "lens", it is deeply different in some aspects. Indeed, the new enabling technologies have a common aspect drastically different: the accessibility (Rifkin, 2015, p.275-311). Indeed, internet, as one of the younger son of the new communication method, i.e. the Massive Online Open Courses, allows anyone to access to information and to produce information. At the same way, 3D printing, and other low-cost manufacturing technologies, allows at a near zero marginal cost to produce simple products. Meanwhile, the renewable energies, together with computer-aided and computer numerical control (CNC) manufaturing machines, are transforming consumer into *prosumers*, i.e. producers plus consumers (Halassi et al., 2019; Inderberg et al., 2018).

1.3 The need of a framework

According to Rifkin the most important transitions in the human history, during the past millenium, was stimulated by innovations on both communication, energy, and transportation aspects. Although he interpreted the ongoing industrial revolution by the use of the same triple matrix, i.e. communication / energy / transportation, in my opinion, the transition we are experiencing in these decades is intrinsically different. Indeed, as revealed by the precursory studies of D. H. Meadows, D. Meadows, et al. (2018) on *The Limits to growth*, by the *Spaceships economy* of Boulding (1966), or by the more recent discussion on the planetary boundaries pointed out by Rockström, W. L. Steffen, et al.

(2009) and Raworth (2017), the ongoing industrial revolution need to face to an *external constraint*. This aspect in particular, as brilliantly discussed also by Rifkin at the end of his book *The zero marginal cost society*, needs new point of views, new approaches, and, in my opinion, a new framework to correctly interpret and read the current transition. Rifkin closed the book with the chapters *the sustainable cornucopia* and *a biosphere lifestyle*, which give a hope for a better future of *abundance*, recalling the words of Wahl (2016). According to the regenerative design school of thought, although a *world of more* (Eisenstein, 2013) could be possible, the current society and economic system, as well as our lifestyle, need to be rethought and *redesigned* to adhere to the new constraints.

But what are the constraints? Rovers, in his book *People vs Resources. Restoring a world out of balance*, would have said *It's materials, stupid!* (Rovers, 2019). Despite the joke, indeed, Rovers worked and investigated in international energy and materials research related to the built environment for decades, for him it is clear that humanity has to face with several planetary boundaries (Raworth, 2017), and some of them are more important and urgent than others. Figure 1.5, adapted from Rovers (2019, p.102), exhibits a reinterpretation of the famous Maslow's pyramid. The original Maslow's pyramid (the top part of Figure 1.5) shows the hierarchy of needs of human being and it was proposed by Maslow as a general theory of human motivation. The foundation of the pyramid, according to Maslow (1943), is based on the *physiological needs* of a human, i.e. the constant supply of air, water, food, as well as the needs for a shelter, and for reproduction; once a person fulfil the physiological needs, the second step is to achieve the *safety needs* - personal security, employment, health. These first two blocks consist of all the basic needs any human being looks for. The next steps, *Love and belonging* and *esteem*, represent the needs of relationships with friends, family, and the relative recognition, respect and self-esteem generated by the human relationships. The four first steps are self-balancing, i.e. once fulfilled a person does not need more, while the top-block of the pyramid, *self-actualization*, might never reach a balance. Indeed, self-actualization, originally coined by Kurt Goldstein, represents the *"desire to become more and more what one is, to become everything that one is capable of becoming"* (Maslow, 1943, p.382). The bottom-part, added by Rovers (2019), instead, shows the hidden part of the Maslow's pyramid. In other words, what is behind the very first block *physiological needs*? It is undoubted that any person needs power/electricity, heat, mass (i.e. resources), food and water to eat and drink, and air to breath. The necessity of power, heat, and resources may change among culture and countries, as well as on weather condition, but generally they are the basic needs to run our economy. This representation is not only about the physiological needs. That's trivial. It's about the priority of the needs. Indeed, how long can anyone live without air? Just a few minutes. And how long without drink water and eat food? From a few days (for water) up to a few weeks (without food). And without resources, heat or power?

On top of the needs pyramid, Rovers discussed a simple indicator to point out the total amount of resources per capita, expressed in land use per capita, according to the ratio

$$\begin{array}{l}\text{Max amount of}\\ \text{resources per capita}\end{array} = \frac{R}{P} \tag{1.1}$$

where R represent the total available resources, and P the total number of people on Earth.

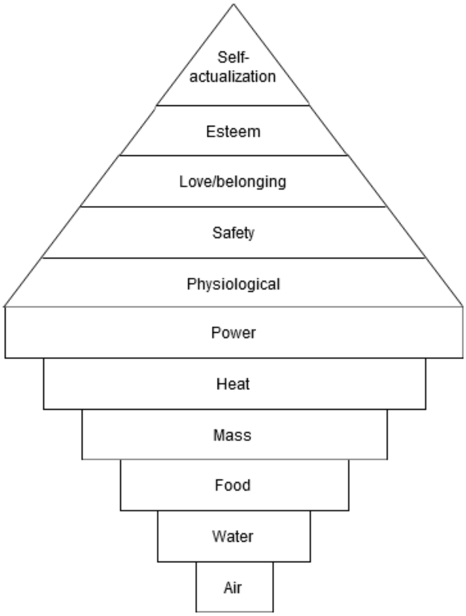


Figure 1.5: Reinterpretation of Maslow's pyramid. Adapted from: Rovers (2019)

R may represent any type of resource (Rovers, 2019, p.161). To satisfy the basic needs of people, Rovers roughly estimated the amount of land per capita, in square meters, necessary for shelter, water, food, energy and so on (Rovers, 2019, p.299-303). For instance, in the Netherlands, for the shelter (i.e. an house) made by bio-based materials, $16m^2_{EL}$ of land per $1m^2$ of useful floor are needed for a typical house unit which last 50 years. The subscript EL represents the embodied land. Thus, roughly speaking, for a $50m^2$ house, more than $800m^2_{EL}$ of land per capita has to be dedicated to this basic human need. Similar calculations show the amount of land per capita for water, food, and so on. Always in the Netherlands, to collect drinking water, from rainwater, let's say, and transport it to people by using solar energy, for instance, only $10m^2_{EL}$ are needed, while for food the estimation range from $1000m^2_{EL}$ to $3000m^2_{EL}$ of land per capita depending on the diet (vegeterian or not) and the type of cultivation (open air or greenhouse cultivation). Finally, for the energy consumption, an average consumption for people is around 1100 kWh per year per person (for heating and ventilation, for instance). Producing the electricity from solar panels (120 kWh/year per m^2) needs around $10m^2$ of solar panels, which, before they generate energy, have to be manufactured. To fabricate $1m^2$ of solar panels, more than $3200m^2_{EL}$ of land are necessary. Thus, supposing the panels themselves last for 25 years, to satisfy the household energy demand per capita for 50 years more than $1300m^2_{EL}$ of land are needed (2 panels * $10m^2/panel$ * $3200m^2_{EL}/m^2$ / 50 years). In total, more than $5000m^2_{EL}$ of land per capita should be used to satisfy only the basic needs for water, food, energy (only heating and ventilation for household), and the shelter. This simple estimation does not aim to be neither satisfactory nor precise and complete, but it aims to provide an insight on the order of magnitude of the embodied land necessary to "survive". It is obvious that in our society, each person needs much more land and resources if all products and services a person daily uses are taken into account. For instance, in the Netherlands, the population density is about $521/km^2$, this means that there are about $2000m^2$ of available land per person. That is not enough to satisfy the basic needs shown in Figure 1.5. Even if The Netherlands cannot be considered a closed system, this simple calculation shows how European countries (in this case the Netherlands) need more embodied lands than the actual country surface and they strongly depend on imports in order to satisfy all the basic needs. As D. H. Meadows, D. Meadows, et al. (2018), decades ago, already concluded with the Limits to Growth report to face the lack of resources the first step is to control the birth, i.e. the population growth, and, obviously to reduce the consumption per capita, in terms of raw resoures, energy consumption, just to name a few.

Another similar treatment, generally applied at the national level, was already emerging at the beginning of the Seventies, thanks to Commoner et al. who introduced the IPAT equation (Commoner et al., 1972; Paul R. Ehrlich and Holdren, 1971; Paul R. Ehrlich and Holdren, 1972). The IPAT equation, in a very concise form, represents the impact of human activity on the environment according to:

$$I = P \times A \times T \tag{1.2}$$

where I is properly the human impact on the environment, P the population, A the affluence, and T the technology. P is simply the population of a certain area (e.g. the world, or a country), the affluence A, instead, reflects the average consumption per capita, while the technology variable T represents the resource use intensity per unit production. For instance, in simplified terms on a national scale, the affluence may be measured in Gross Domestic Product (GDP) per capita and the technology in $tCO_2/\$$. The IPAT model, as other similar models, has been largely criticized as *mathematical propaganda* because it is a rough estimation, a snapshot of the human pressure on Nature in a certain year. Despite the critics, the IPAT model is still used to evaluate the environmental impact if anything will change (McAfee, 2019, p.62).

Finally, a worldwide adopted methodology is the so-called *Ecological footprint* (EF), i.e. the required lands (terrestrial and marine) necessary to support human activities. The underlying concept and idea was originally developed in the Nineties by Rees (1992) as an accounting methodology for the sustainable development to evaluate for a given country, city or territory if it was able to be sustained indefinitely by the local available resources and lands. The first calculation of the Ecological Footprint was conducted by Wackernagel et al. (1997) and later continued by the Global Footprint Network (GFP) that launched in 2003 the National Footprint Accounts (NFA). Basically, the Ecological Footprint Analysis (EFA) relies on two main measurements: 1) the *Ecological Footprint* (the demand), i.e. the amount of lands necessary to satisfy the total demand for a given year and country (or for the entire Planet), and 2) the *Biocapacity* (the supply), i.e. the regenerative capacity/the ecological ceiling of a given country or, in other words, the amount of bioproductive land (terrestrial and marine area) available to supply the services (produce resources or absorb CO_2). More precisely, an Ecological Footprint

Analysis measures the Ecological Footprint (EF), i.e. the land appropriated and used by human activities (e.g. built environment, crop and grazing lands), with respect to the Biocapacity of the Planet, i.e. the amount of bioproductive and sea areas available to produce the needed goods. Through the EFA can be calculated the so-called *Earth Overshoot day*, i.e. the day in a year when the Earth theoretically exceeds the biocapacity and start to consume more resources than the available ones. It can be simply computed as the ratio between the Earth's Biocapacity and the Humanity's Ecological Footprint multiplied by 365 days. According to the NFA in 2008 we consume 1.5 planets while in 1961 only 0.7 planets; thus in the Sixties the Ecological Footprint was not exceeding the available resources (Borucke et al., 2013). In 2017 (the last year with available data) the available resources for the year finished the July 29 (GFN, no date).

Thus, in conclusion, what should be a proper framework in order to take into account the real constraints for the human being and, at the same time, to be able to fit with the ongoing industrial revolution and with the idea of a sustainable development for future generations? In next subsection, the above-mentioned communication / energy / transportation matrix and other common frameworks are presented and briefly described. Each one has its advantages and drawbacks. Each one is fitted to describe innovation processes - the triple matrix (Rifkin, 2015) - to analyze subsistence local economies - the energy-water-food nexus (Chi Zhang et al., 2018) - or to guide us towards a sustainable future (UN, 2020).

1.3.1 Energy, transport, communication

Each past industrial revolution, as well as the ongoing third revolution can be analyzed in terms of the Rifkin's triple matrix. For the sake of clarity, Table 1.1 summarizes the most relevant enabling technologies according to the Rifkin's framework, as reported in his book *The zero marginal cost society*.

Table 1.1: Enabling technologies for industrial revolutions. According to Rifkin (2015)

	Communication	**Energy**	**Transportation**
Feudal to market	- printing press	- windmill - watermill	- sea transport
1st industrial revolution	- telegraph - steam-powered printing press	- steam engine	- train and railroads
2nd industrial revolution	- oil - electrification	- telephone - radio	- combustion engine (car, truck)
3rd industrial revolution	- internet & social media - MOOC	- renewable energy	- 3D printing

1.3.2 The Sustainable development goals

The text of this subsection is partly based on and adapted from *Easy Open Data* (Dario Cottafava, 2018).

On September 25th 2015, the United Nations adopted 17 goals[3], within the "Agenda

[3]GOAL 1: No Poverty; GOAL 2: Zero Hunger; GOAL 3: Good Health and Well-being; GOAL 4: Quality

for Sustainable Development" (UN, 2015a), in order to protect the planet, to end poverty, as well as to ensure prosperity and create a global partnership for sustainability. Each goal is based on specific targets and indicators to be achieved before 2030. More precisely the Sustainable Development Goals (SDGs) consist in 17 Goals, 169 targets and more than 240 indicators. The SDGs have been adopted as an evolution of the Millenium Development Goals (MDGs), adopted within the UN Millenium Declaration in September 2000 (UN, 2000). The MDGs were more focused on social sustainability and on the fight to extreme poverty with respect to the SDGs. In fact, more precisely, the 8 MDGs were: 1. eradicate extreme poverty and hunger, 2. achieve universal primary education, 3. promote gender equality and empower women, 4. reduce child mortality, 5. improve maternal health, 6. combat hiv/aids, malaria and other diseases, 7. ensure environmental sustainability, 8. global partnership for development.

On the contrary, SDGs provide a more general and integrated framework for a sustainable development and aim to create a collaborative framework among research, education, society and industry at both international, national and local scale. In fact, SDGs have been designed to stimulate collaboration among completely different fields. The interactions and interlinkages between SDGs is not clearly declared and explicit in their definition. For this purpose several papers, in the past years, analyzed the interdependencies in order to identify and promote a general model able to explicit and highlight all possible emerging interactions.

The SDGs have been written and thought as a fully connected network of goals in order to improve multidisciplinary collaborations among sectors and different fields. Each goal, through related targets and indicators, is tied with other goals with positive or negative impacts depending on various factors. Actually there are several research studies focused on these interconnections. For instance, *A guide to SDG interactions: from science to implementation* book (Griggs et al., 2017) published by the International Council for Science (ICSU) and based on the work of Måns Nilsson et al. (2016), explores the interconnections of 4 SDGs with all the others with a scoring systems. A more recent study by Weitz, Carlsen, et al. (2018) shows the interactions matrix among 34 targets in Sweden based on a 7-score system (-3,0,+3). The authors also analyzed and identified cluster of targets which positive influence each others, creating a sort of virtuous circle. These types of studies are necessary for policy and decision-makers in order to have useful tools to invest within a field or another one. Finally, Coopman et al. (2016) proposed three categories of interactions - relying, enabling and supporting - while Le Blanc (2015) proposed a brute force approach starting from the common keywords within the targets.

More in general, SDGs are based on the three Es principles - environment, economics and equity - and both the scientific community and policy makers underlined the necessity for a systemic approach. Recently Glass et al. (2019) analyse the role of the governance, defined as the *"fourth pillar of sustainable development"* expanding the three Es model.

Education; GOAL 5: Gender Equality; GOAL 6: Clean Water and Sanitation; GOAL 7: Affordable and Clean Energy; GOAL 8: Decent Work and Economic Growth; GOAL 9: Industry, Innovation and Infrastructure; GOAL 10: Reduced Inequality; GOAL 11: Sustainable Cities and Communities; GOAL 12: Responsible Consumption and Production; GOAL 13: Climate Action; GOAL 14: Life Below Water; GOAL 15: Life on Land; GOAL 16: Peace and Justice Strong Institutions; GOAL 17: Partnerships to achieve the Goal

Using multiple regression they correlated the achievement of each SDG at national level to four different aspects related to the governance of a Nation, i.e. participation, policy coherence, reflexivity, adaptation and democratic institutions. Their results highglight how a *good* governance, in terms of the four considered aspects, has a positive impact for the achievement of the SDGs.

Although the effort of the academic community in the last five years, due to the high complexity of analysing the interconnections among more than 200 indicators a recognized standards to study the interactions among SDGs does not exist yet. Hence, in next subsection, a simpler framework, the water-energy-food nexus, proposed by Weitz, Måns Nilsson, et al. (2014) will be briefly discussed.

1.3.3 Food, Energy, and Water

Several scholars started to adopt various *nexus*, i.e. *an important connection between the parts of a system or a group of things* (Cambridge dictionary, 2020), to study the relevant relationships among fundamental "units" for our society, such as water, materials, energy, food, and so on. Currently, there is not yet a common definition of nexus. Chi Zhang et al. (2018), through a literature review, identified a nexus both as a way to describe a system and as a systematic analysis approach to evaluate a system. A nexus describes the inter-relations among different sectors or subsystems of the system analyzed, and according to Chi Zhang et al. (2018) may be defined as:

> **Definition 1.3.1 — Nexus.** The nexus is put forward to call for an integrated management of the sectors by cross-sector coordination in order to reduce unexpected sectorial trade-offs and promote the sustainable development of each sector.

For instance, the food-energy-water (FEW) nexus represents the interdependencies among food, energy, and water, in their production, use and End of Life phases (Y. Liu et al., 2016) in global or regional evaluation. The FEW nexus emerged recently as the need of overcoming blind studies on singular field, e.g. only by considering energy or the food system (Y. Zhang et al., 2015). The FEW nexus came popular in 2008, during the World Economic Forum (WEF) where the sustainable development was discussed in terms of the food-energy-water nexus (Chi Zhang et al., 2018). A few years later, in Bonn in 2011, during the launch of *"water-energy-food security nexus: solutions for the green economy"*[4] conference, organized by the German Federal Government, with the World Economic Forum, the World Wildlife Fund (WWF) and the International Food Policy Research Institute (IFPRI), the necessity for a more systematic view was confirmed. It should consider interconnections among social, economical, and environmental subsystems. Subsystems' interconnections imply, in particular, that each subsystem directly affects the others; thus, the analysis of a nexus is needed to avoid negative collateral effects of policies and direct actions (P. Zhang et al., 2019). In the case of energy, water, and food this necessity is, indeed, of primary importance due to the high risk for people caused by a lack of these resources, even if temporary and short in time (Venghaus et al., 2018). On this purpose, the Food and Agriculture Organization (FAO) recognized as the FEW nexus describes *"the complex and inter-related nature*

[4] `https://www.water-energy-food.org/news/bonn2011-bonn-launches-nexus-perspective`

of our global resources systems" (FAO, 2014). The need for a systematic approach in treating essential resources for society and for ecosystem was clearly demonstrated by the rebound effect due to the incentives on biofuel in the first decade of the XXI century. The rapid exploitation of agricultural land for the production of biomass crops to produce biogas and biofuel (the aim of the incentive was to limit and reduce the climate change) had a negative effect on biodiversity (Meehan et al., 2010) and linked the price of food production with the fuel global price, perhaps causing political instability of poor countries. Lagi et al. (2011) analyzed *The food crises and political instability in North Africa and the Middle East* between 2008 and 2013 by identifying a correlation between earlier riots in 2008 and global food price peaks. As a consequence, they concluded that biofuel policies needed to be urgently reconsidered in order to face the social challenges of poverty, and of the political protests. There exist dozens of nexus; two, three and four nodes nexus depending on how many sectors are considered. Common two-, three-, and four-node nexus are shown in Table 1.2.

Table 1.2: Two, three, four-node nexus.

Nexus size	**Considered sectors**
two-node	energy-irrigation (Mukherji, 2007) energy-water (Marsh et al., 2007) food-energy (Walsh et al., 2018)
three-node	food-energy-water (Chi Zhang et al., 2018) water-energy-climate (Mu et al., 2009) land use-climate change-energy (Dale et al., 2011) environment-water-climate (Groenfeldt, 2010)
four-node	water-food-energy-climate (Waughray, 2011) climate-land-energy-water (Hermann et al., 2012)

In conclusion, the FEW nexus, like other nexus studied in the academic literature, reveals the necessity for a general framework and of a systematic approach to face with ecological systems. In the case of the FEW nexus, or other similar nexus, the choice of the analysed category directly depends on the Maslow pyramid of essential physiological needs as depicted in 1.5.

To conclude, which category should be included in an assessment and evaluation framework taking in mind clarity, simplicity and completeness? Which are the fundamental aspects to be considered to support decision, and policy, makers in wisely manage a local territory? In the next section, and in general within this work, such questions, and many others, will be treated. Starting from framing the current challenge in a general and global way, the most relevant aspects related to the *lack of resources*, the *planet boundaries* and the, possible, *shortage of available renewable energy* issues are presented and discussed, within the circular economy umbrella. Precise methodologies, tools, and approaches for the Circular Economy are introduced and explained, and, then, applied to particular case studies and examples.

1.3.4 Energy, materials, information

At this point, the main limitations of the current economic system should be clear. As originally introduced by Kenneth Boulding in “The economics of the coming Spaceship Earth”, the Earth, our house, should be considered as a closed system (Figure 1.3) where each material is worthwhile and cannot be wasted.

Energy, apparently, should not be a main issue considering the ongoing energy transition from fossil fuels to renewable energy because of the constant input flow of solar energy. Apparently, it should not. According to the rough estimation made by Rovers in his book *People vs Resources. Restoring a world out of balance* (p.299-303), even the production of solar energy panels needs resources, in the Rover’s treatment calculated in embodied land. Moreover, as it will be discussed in next chapters, the newest renewable energy technologies, from wind turbines to photovoltaic solar panels, need Rare Earth (REE) materials and the production process itself, as well as the recycling of materials, could be very impactful. Thus, starting from the thought of H. T. Odum (1996), as also described by Rovers, an all-encompassing variable to take into account the planetary boundaries should be based on *emergy* (H. T. Odum, 1996), or on the *exergy* (Koroneos et al., 2012). Emergy theory was introduced by Odum H. T. Odum (1996) as an environmental accounting and decision making tool. Emergy is the available, direct or indirect, energy used to produce a product or a service. Similarly, exergy is the available energy, the useful work, in a system (Goran Wall et al., 1986). As depicted by Goran Wall et al. (1986), although the energy flow passes through the Earth, the available energy, i.e. the exergy, is much lower, and a part of exergy is dispersed in every real irreversible process, according to the 2nd law of thermodynamics. Thus, in a society and an economy based on the transformation of materials into products, and of energy from one type to another one (e.g. from kinetic energy to electricity or heat), a second constraint to be taken into account should be related to energy, or exergy, flows.

Finally, why has information to be included in a general framework for the circular economy? Information is not a limited quantity. On the contrary, information system (Britannica, 2020) could support a wise management of the global resources through the use of *decision support systems* (DSS) (Keen, 1980), or *knowledge management systems* (KM) (Girard et al., 2015). The hierarchy of data, information, knowledge, wisdom (DIKW), as illustrated in figure 1.6 (Ackoff, 1989; Bernstein, 2009), is the theoretical foundation, the basic framework to bring humanity, or simply an organization, towards a sustainable resource management. Moreover, information, in its widest meaning, has been largely proved by researchers and practitioners to activate behavioural change processes in people (Cottafava et al., 2019) and to increase connectivity throughout the world, and, thus, it may be an enabler for the Circular Economy (Circle Economy, 2019).

Recalling *The Limits to growth* and the suggestions presaged in the conclusion of the report, information, knowledge and wisdom should be the only way to avoid a sudden collapse of human population.

But how?

In the world system the natural limits are represented by the depletion of natural resources, the lack of enough food per capita, and by the environmental pollution. According to the authors of the report, all three limits are strictly bounded to the world

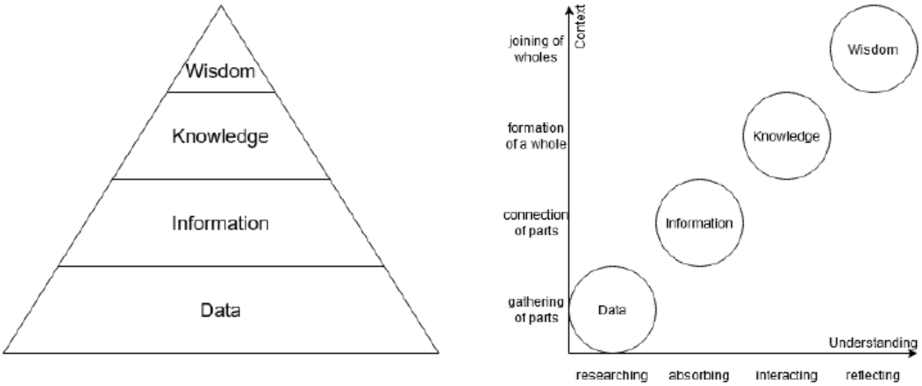


Figure 1.6: Data, information, knowledge, wisdom hierarchy. Adapted from: Bernstein (2009)

population, that without control policies, tends to grow exponentially reducing the available resources. The population, as well as pollution generation or the industrial growth, without regulating and balancing feedback loops, will grow until the achievement of one, or more, of the planetary boundary, consequently causing a sudden drop in the considered variable. In their opinion, the only solution to face up the exponential growth is the introduction of a new causal link between, for instance, the death rate and the birth rate in order to balance and control the population. The same control is necessary to manage the industrial growth, the pollution or the resource exploitation to maintain the world system into a dynamic global equilibrium (D. H. Meadows, D. Meadows, et al., 2018, p.155-175). Although strict population control policies have been discarded (this aspect will be discussed in detail in chapter 4), achieving a dynamic global equilibrium with the planet is still a necessity. Thus, one more time, information correctly enters into an energy-material-information nexus, not as a constraint or a barrier in human development, but as an enabler, the unique solution, to maintain humanity in the so-called safe and just space. Concluding, two further concepts that will be discussed in more details in next chapters (see chapters 5 and 6) should be introduced to understand the role of information in the proposed framework: resilience and adaptation. Both terms derive from the idea of facing the current environmental crisis by planning the positive response of the ecosystem to the unavoidable sudden, and ever increasing, shocks due to the climate change. Both terms, and the corresponding strategies that can be adopted by the humanity, assume that mitigation strategies, i.e. strategies aimed at reducing the generated impacts, are not enough to cope with the climate change. Both terms need to predict future scenarios and events and to plan regenerative solutions able to bring back rapidly the ecosystems to a stable and in equilibrium state.

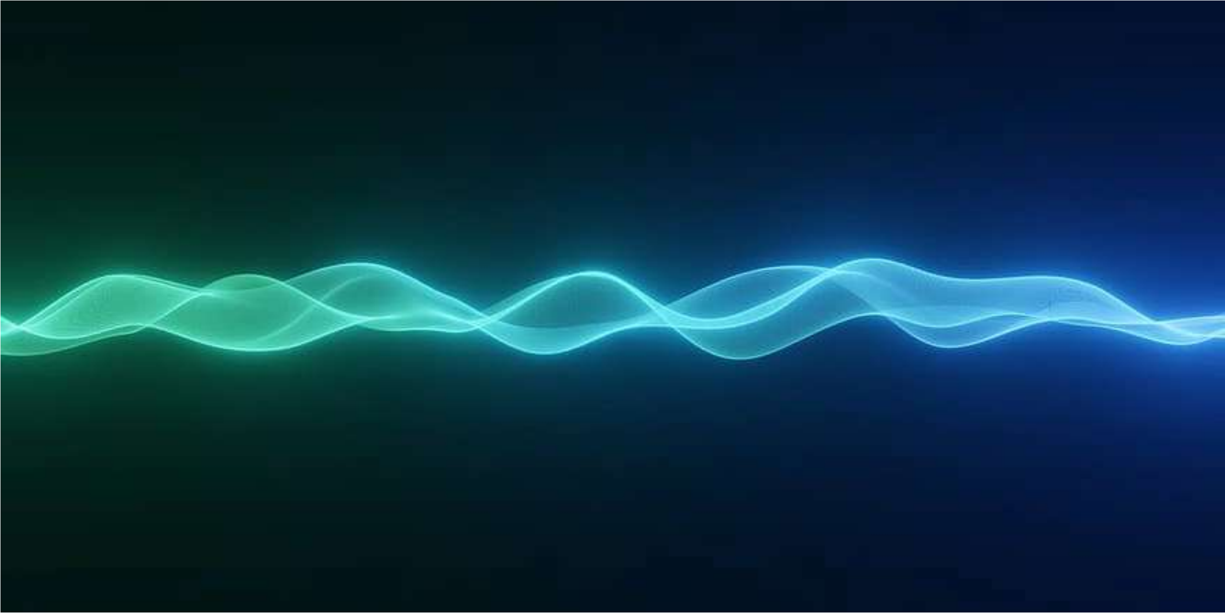
Concluding, in this chapter we have briefly introduced the basic concepts and a few of the past theories facing with planetary boundaries and the limits to growth necessary to understand the current ecological crisis. In the last paragraph we discussed the energy-material-information framework that will be used to discuss evidences about the environmental constraints and on how to envision a resilient and adaptive ecosystem for our Planet.

In the rest of the book the energy-materials-information framework will be adopted as a key for reading and understanding the potentiality and the limitations of the circular economy in order to define how a *Circular Thing* has to be defined.

In part I the rationale of the proposed energy-materials-information framework is provided. Climbing on the shoulders of giants as Donella Meadows, Kenneth Boulding, Herman Daly, Howard Odum, Johan Rockström, Elinor Ostrom, Jeremy Rifkin, and many others, in the first part of this book, I attempt to interpret the new emerging paradigm of the circular economy, by linking the *Collaborative Commons*, as defined by Rifkin, the *ecological transition* and the *planetary boundaries*, as described by the environmental economics school of thought.

In part II, in chapter 5, the humankind challenge is introduced and, after a brief introduction on circular economy, "what is a theory" - and "how to put the necessary basis to develop it" - is discussed according to the Information Systems (IS) school of thought. The necessity to *design a theory* is highlighted in order to move from the emotional current hype and trend about the circular economy towards a more robust formalism and interpretation. Subsequently, the circular economy is described in much more detail (chapter 6), focusing on the underlying concepts and the previous schools of thought. In chapter 7, an overview on the assessment methodologies is presented, discussing the most adopted tools and methodologies, from Design for Disassembly criteria to circularity indicators, from the Systems Dynamics to the Input-Output models.

Finally, in part III, a few applications and examples are presented in chapter 8, while in chapter 9 a general Information System artifact is defined to assess a *Circular Thing*.



2. Energy

Energy, from Greek *energeia* (from *en*, "at", and *ergon*, "work, action"), means "activity, action, operation" and it was firstly used by Aristotle to express "actuality, reality, existence", and lately misunderstood as "force of expression" (Online Etymology Dictionary, 2001). The Greek definition was a quite broad philosophical and abstract concept. The modern definition of energy, instead, traces back to the XVII century. Although there is still a debate and an open controversy on who first introduced the modern concept of energy and its conservation law, it is undoubtedly Leibniz one of the first contributors. He discussed the *"vis viva"* term (from Latin "living force") to describe the actual concept of the Kinetic energy, i.e. the energy of an object due to its motion; originally, indeed, Leibniz observed that in many systems, composed by many objects, the quantity $\sum m_i v_i^2$ was conserved (Iltis, 1971) where m_i is the mass of the object i and v_i its velocity. He proposed that objects, due to their motion, may have a living force (*vis viva*), while objects at rest possess a dead force (*"vis mortua"*), which eventually may be transformed into *vis viva* (Lehrman, 1973). Generally defined as a property of an object to do work, its theoretical meaning is rooted in and inseparable from the conservation of energy (Feynman et al., 1965), originally discussed by Mayer, Joule, and Helmholtz (Müller, 2007, p.171) and later stated as the 1st law of thermodynamics.

The energy concept, thus, is strictly tied to the ability to do work; there exist many forms of energy which can be exploited and used to support the human activities: thermal, chemical, electrical, electromagnetic, or kinetic energy, just to name a few. Energy can be transformed from one type into another one through many different artificial or natural

Table 2.1: Energy transformation processes. Adapted from Armaroli et al. (2017, p.21)

From / to	**Thermal**	**Chemical**	**Electrical**	**Electromagnetic**	**Kinetic**
Thermal		endothermic reaction	thermoionic process	incandescent light bulb	combustion engine
Chemical	exothermic reaction		electric battery	chemi / bio luminescence	muscle / engine
Electrical	electrical resistor	electrolysis		electroluminescence	electrical engine
Electromagnetic	solar collector	photosynthesis	solar photovoltaic		solar sails / magnetic poles
Kinetic	friction	stirring	alternator	accelerated electrical charge	

processes as summarized and listed in Table 2.1. Table 2.1 is not exhaustive; indeed, there are many other forms of energy such as the potential energy, the energy of an object due to its physical position, which can be transformed easily into kinetic energy, the nuclear energy, which exploits the energy of the nuclei of atoms to produce thermal energy, and so on. Typically, every real process implies an energy transformation. With the words of Goran Wall (2009) *"everything that happens involves conversion of energy"*. Not all forms of energy are equivalent. A quality hierarchy of energy types has been widely discussed in the literature (H. T. Odum, 1988; Ohta, 2012; Göran Wall, 1990). For instance, according to Göran Wall (1990), the highest quality is related to mechanical (kinetic), electrical, and chemical energy (with the highest exergy), while the lowest quality refers to heat at room temperature (with the lowest exergy). Hot steam, or the sunlight, instead, represent an average quality. Similarly, H. T. Odum (1988) classified the energy production sources, both renewable energy (e.g. sunlight, wind, tide) and fossil fuels, up to the amount of energy within food and even information. Table 2.2 shows the hierarchy according to Goran Wall (2009), Ohta (2012, p.90), and H. T. Odum (1988). Ohta and Goran Wall (2009) classified the energy type in terms of exergy, i.e., roughly speaking, the maximum useful energy with respect to surrounding environment, while H. T. Odum studied the hierarchy in terms of the emergy, i.e. the amount of energy consumed in a trasformation to make a product or a service (measured in emjoules).

From the discussion about energy quality, as pointed out in the treatment of H. T. Odum (1988) and in most recent studies (Llamas et al., 2019), it clearly emerges that from heat up to fossil fuels, from electrical energy to food and human services, a necessary energy amount may be attributed to every object, or service.

Thus, what is the intrinsic difference among potential, wind, or tide energy, a fossil fuel, as petrol or coal, and a laptop made by dozens of different raw materials and metals? A basic classification of resources should be done in terms of stocks (deposits and funds) and flows. Figure 2.1 exhibits the fundamental distinction to be taken into account to analyze an ecosystem in terms of resources. Flows represent such resources that depend only on the total flow and they can be exploited without limit in time. In other words, in relation with the sustainable development definition, today's use does not

Table 2.2: Energy quality ranking (different units of measure). According to Ohta (2012), Goran Wall (2009), and H. T. Odum (1988)

Ohta	**Wall**	**Odum**
Conversion Efficiency (0-1)	Exergy factor (0-1)	Solar transformities ($semj/J$)
electromagnetic	mechanical	information
mechanical	electrical	human services
photon	chemical	food
chemical	nuclear	consolidated fuels
heat	sunlight	mechanical
	hot steam (400 °C)	electrical
	district heat (90 °C)	unconsolidated organic matter
	heat	wind kinetic energy
	thermal radiation	sunlight

affect tomorrow's availability. *Flows* are, for instance, sunlight, wind, ocean currents. On the contrary, *stocks* use directly affects tomorrow's availability. Stocks are further subdivided into *deposits* (dead stocks) and *funds* (living stocks). The basic difference is based on the regeneration time. Deposits (e.g. fossil fuels, minerals) regenerate the stock in a longer time scale with respect to the human life, while funds regenerate themselves in a time range comparable with human life (e.g. months, years, centuries). Thus, deposits tends to disappear as they are exploited, while funds, if managed wisely, i.e. the extraction rate must not exceed the regeneration rate, may last forever (Perman et al., 2003, p.11-12). According to this definition, the commonly renewable energies (e.g. biomass, solar energy, ...) both derive from funds, also called *renewable flows* (Göran Wall, 1990), and from natural flows.

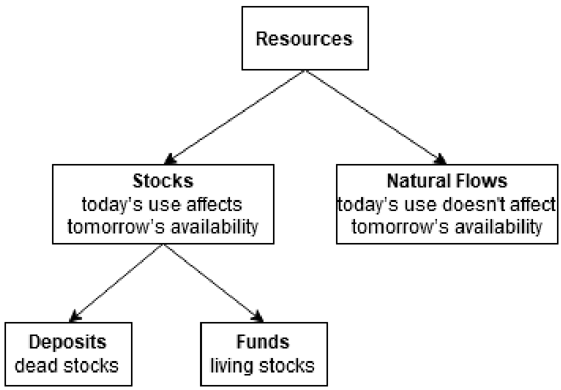


Figure 2.1: Stock and flow classification. Adapted from Göran Wall (1990)

In the last thirty years, the Total Energy Supply (TES) world supply, according to the International Energy Agency (IEA), is constantly increasing IEA (2020a). According to the IEA (2020b), the TES is a global index which, for a given country, is calculated as:

$$TES = production + imports - exports \pm stockchanges \tag{2.1}$$

Figure 2.2 shows the world TES per energy source - coal, natural gas, nuclear, hydro, wind/solar, biomass and waste, and oil - from 1990 to 2018. The TES has increased from the 8000 Mtoe in 1990 to more than 14000 Mtoe in 2018, with an increase of more than 70% with respect to 1990. The global picture is not reassuring at all. Moreover, although the huge effort and investment on renewable energy, especially in the last 10-15 years, the energy supply from renewable sources, as hydro, solar, wind and biomass, slightly increased from the 12.8% of the total supply in 1990 to the 13.8% in 2018 (Figure 2.3). Not a huge achievement. In particular, solar and wind energy supply share increased by 1.6%, hydro by 0.4%, but the biomass and waste supply decreased from 10.3% to 9.3% of the total energy supply. Thus, the non-renewable energy supply slightly decreased; such reduction is mainly due to a reduction in the supply of oil (from 36.9% to 31.5%). On the contrary, coal and natural gas energy supply increased from 25.3% to 26.9%, and from 19% to 22.8%, respectively. The coal energy supply increase is mainly due to the fast development of the economy of China and India, which quadruple their coal supply since 1990 (+270% for China, and +347% for India) and together accounts for the 62.5% of the world coal energy supply (51.7% the China, and 10.8% the India).

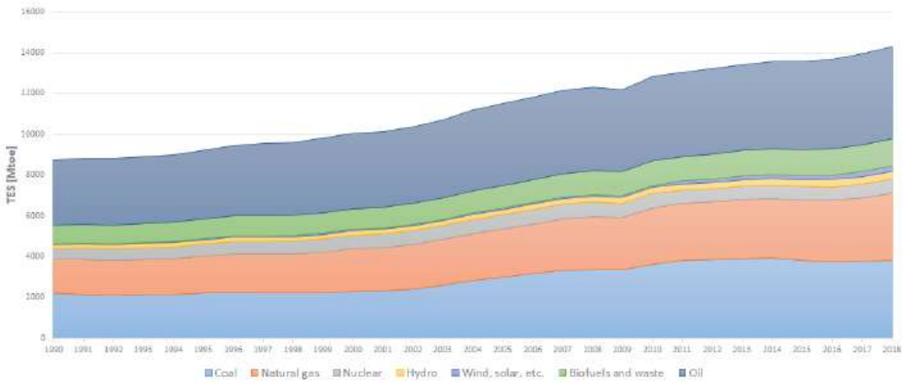


Figure 2.2: Total Energy Supply (TES), World 1990-2018. Data source: (IEA, 2020a)

Not so encouraging. Recalling the Aristotelian physics (Sokolowski, 1970), we are still living in the *fire* era.

Focus 2.1 — Aristotelian physics. Aristotle classified the world into a sublunary region, made of four elements - fire, water, air, and earth - and one heavenly region, made of *Aether* (Geoffrey Ernest Richard Lloyd et al., 1968, p.134-135). In his thought, each element was described in terms of hot/cold and wet/dry quality, and

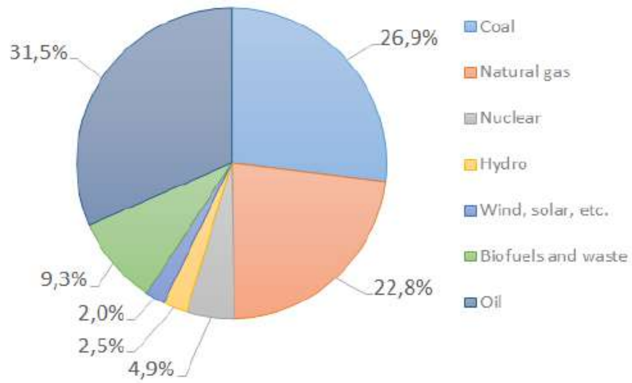


Figure 2.3: Total Energy Supply (TES), World 2018. Data source: (IEA, 2020a)

phase transitions between one state to another one were described in terms of a change between the contraries, hot to cold or viceversa, or, wet to dry (Geoffrey Ernest Richard Lloyd et al., 1968, p.167-169). The changes were discussed as a linear up/down motion between opposites. An interesting insight from Aristotle's thought, with respect to the current debate around the circular economy and, more in general, about the sustainable development was the description of the motion within the heavenly region. Indeed, in his opinion, only in the Aether a circular motion, not enforced, was possible forever (p. 136-137). Despite his idea of Aether to explain an eternal motion was derived on completely wrong assumption to describe celestial motion, it is interesting to find a similarity with current religious concepts, and more pragmatically, with circular economy. Till now, from Aristotle to Buddhism (Pecunia, 2011), circularity has always been seen as the way to explain eternal and continuous motion, i.e. the rationale for a God or a divine entity. Only recently, circular and eternal motion moves from the divine to the "terrestrial" sphere. *"If indeed circular organization is sufficient to characterize living systems as unities, then one should be able to put it in more formal terms"* stated Maturana et al. (1991, p.xvii) when they introduced the term *autopoiesis* to define a circular organization. From the autopoiesis concept to the most recent circular economy, for the first time in history, an attempt to, first explain and, then control, something eternal is occurring.

By the way, returning back to the Earth, the linearity of human society and its exploitative relationship with the Nature, especially in the last two hundreds years, may be pictured, in Aristotelian physics, as the *fire* era. The current energy transition, as described by Armaroli et al. (2017, p.169), implies a motion from the fire to water, air, and earth. Perhaps, the next step, that only now we are trying to decode, should bring *us* back, or better saying *Nature*, to the heavenly region. ■

2.1 Fossil fuels

As discussed in chapter 1, from the end of the XVIII century, first, the coal with the invention of the steam engine and its diffusion during the first industrial revolution, and, second, the oil/petrol with the diffusion of the combustion engine during the second industrial revolution, have brought very quickly the human society to be very dependent on fossil fuels. The large exploitation of fossil fuels in the last two hundreds years can be understood looking at the Table 2.3. Table 2.3 summarizes the energy density, per kg, or per m^3 in the case of the natural gas, of the most common used fossil fuels. Each fossil fuel has a huge embodied energy. One kilogram of crude oil may be burned to obtain about 42-44 MJ (11-12 kWh).

Table 2.3: Energy density of fossil fuels

Fossil fuel	MJ/kg	MJ/m^3
anthracite	31-33	
bitumen	20-29	
lignites	8-20	
peat	6-8	
crude oil	42-44	30000-40000
natural gas[1]		29-39

[1] at atmospheric pressure.

Current oil reserves consist in two main categories, conventional and non conventional. The former refers to the classical drilling technique, i.e. the oil wells (both on land and offshore), while the latter refers to the so-called heavy oil, which can be extracted from the *tar sands* or from the *shale oil*. The tar sands funds mainly lie in Canada and Venezuela; the extraction of the oil from this sands is environmnentally dangerous due to the low density and concentration. The shale oil, instead, consists in rocks mixed with oil, deep underground (Armaroli et al., 2017, p.91-95). Natural gas and coal, are also widely used - the coal especially in China and India and natural gas in Europe and America - but, as depicted in Table 2.3, the embodied energy of gas (at atmospheric pressure) is much lower than the liquid oil. A recent technique, mostly used in North America, to recover the so-called *tight gas* is the hydraulic fracking. Fracking techniques allows to recover oil and gas from very deep deposits (1-3km) in the ground by injecting high pressure water or air in the ground (Armaroli et al., 2017, p.96-99). This technique is highly criticized for its environmental impact and for inducing local earthquake (Ellsworth, 2013). Finally, coal is still used in developing countries and in China, but, in the XXI century it is an option that is gradually banned from all countries due to its high impact on climate change and carbon dioxide emissions (Armaroli et al., 2017, p.101).

Figure 2.4 shows the known reserve (R) over the yearly production (P) for coal, natural gas and oil. The R/P ratio, expressed in years, represents the maximum duration of existing proven reserves. The global picture is quite impressive. Worldwide oil and gas reserves will completely finish in 50 years, while coal reserves apparently will

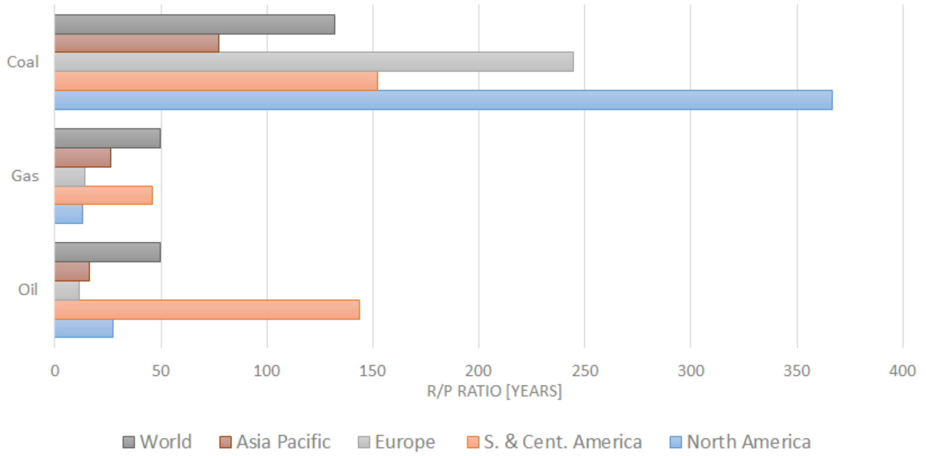


Figure 2.4: Reserves-Production (R/P) ratio. Data source: (BP, 2020)

last over than one hundreds years. If one consider only Europe, or North America the situation is even worst. Indeed, oil deposits will be exhausted in less than 15 years, while gas reserves in North America may last for at least 25 years. It is clear that known fossil fuels are running out, and new technologies and solutions are needed to face up the coming shortage of supply, as envisioned by D. H. Meadows, D. Meadows, et al. (2018) more than fifty years ago.

Focus 2.2 — The Hubbert peak theory. In 1956, in his famous paper "Nuclear energy and the fossil fuel", Hubbert et al. (1956) discussed for the first time a theory to predict the oil and nuclear production peak due to the depletion of available known global reserves. He presented a theory to explain the shape of the cumulative production starting from two simple considerations: 1) *for any production curve of a finite resource of fixed amount, two points on the curve are known ... at* $t = 0$ *and at* $t = \infty$*. The production rate will be zero when the reference time is zero, and the rate will again be zero when the resource is exhausted* (Hubbert et al., 1956, p.12), and 2) the cumulative production Q up to a given time t is equal to:

$$Q = \int_0^t P dt = \int_0^t \left(\frac{dQ}{dt}\right) dt \tag{2.2}$$

where $P = {}^{dQ}/_{dt}$ is the production rate. Thus, the *ultimate production* Q_{max} is given by the integral from $t = 0$ to $t = \infty$. In other words the production rate of a finite resource must begin and end at 0, passing through *one or several maxima*. Usually, but not always, the cumulative production of a finite resource follows a logistic curve.

According to Cavallo (2004), the cumulative production $Q(t)$ at time t is defined as:

$$Q(t) = \frac{Q_{max}}{(1+ae^{-bt})} \tag{2.3}$$

where Q_{max} is the ultimate production, i.e. the total resource available, and a, b two constants. The Hubbert curve, i.e. the production rate over time, is the derivative of Eq. 2.3, and the maximum production rate, $dP/dt = 0$ occurs at

$$t_{max} = -\frac{1}{b}\ln\frac{1}{a} \tag{2.4}$$

Hubbert estimated the trend of a few fossil fuels (e.g. coal, oil, and natural gas) based on the production rate of the previous decades and the known reserves for a few states of the United States of America. Despite in its original paper Hubbert included very large constraints on initial and final production rate and defined a very general function P, and he correctly stated that P may pass *through one or several maxima* (discussing as well an example with two maxima for the state of Illinois), the model, due to the wrong predictions he discussed in detail, opened a lively academic debate (Hemmingsen, 2010; Priest, 2012). In particular, he estimated that the global peak of oil and coal production would occur around 2000 and 2150, respectively. Roughly speaking, the Hubbert model, in its original general definition of eq. 2.3, should be considered still valid but with several limitations, mainly due to the difficulty to precisely quantify global reserves of fossil fuels, as recently discussed by Jowitt et al. (2020). Indeed, the past decades demonstrated as the demand increases, and consequently the price of a fossil fuel, mining companies tend to invest more on exploratory analyses in order to exploit deeper resources or to discover new ones. Moreover, political, economic factors, as well as the introduction of new mining and drilling techniques or other unpredictable events, may noteworthy affect the findings of the model. ■

The R/P ratio should be enough to convince on the urgency to move out from fossil fuels dependency, although largely debated (Jowitt et al., 2020). Focus 2.2 briefly described the Hubbert peak theory for fossil fuels and its failure. Since the shortage of fossil fuels cannot be accurately predicted, which is the real limit? To answer such a question, one should look at their impact on climate change, for instance. Indeed, what is the amount of carbon dioxide produced by exploiting coal, oil, and gas? The combustion of 1 g of coal produces about 3.66 g of CO_2, of 1 g of gasoline, i.e. the octane C_8H_{18}, generates about 3.08 g of CO_2, while 1 g of methane (CH_4), the most common used natural gas, when burnt, creates 2.74 g of CO_2 (Armaroli et al., 2017, p.120-121). Nowadays, each year more than 30 billions tonnes of CO_2 are introduced into the atmosphere by human activities (BP, 2020), mainly due to the combustion of fossil fuels. Figure 2.5 shows the annual CO_2 emissions into the atmosphere from 1965 to 2019. In the last fifty years the global CO_2 emissions tripled, with a sudden rise in the first decade of the XXI century, despite the open debate on climate change and all the IPCC advice.

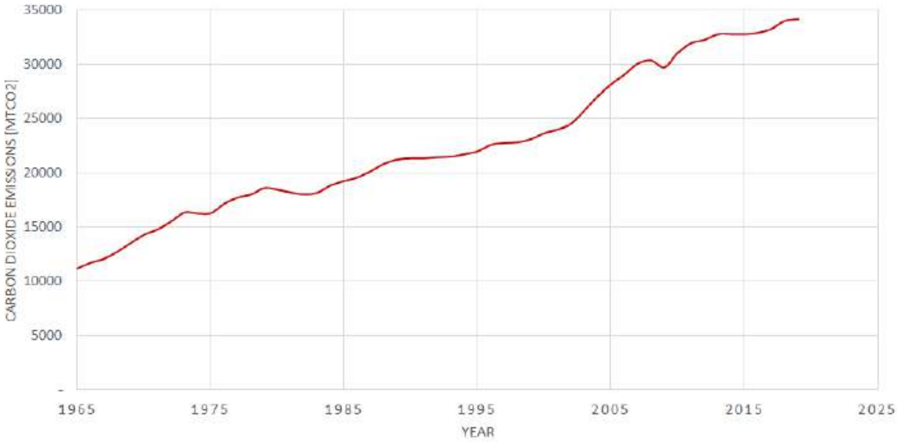


Figure 2.5: Carbon Dioxide global emissions from 1965 to 2019. Data source: (BP, 2020)

2.2 Energy transition

By using the word of Armaroli et al., renewable energy means *energy from water, air, and earth*. In the last decades, impressive results have been achieved. In 2016, for the first time, Germany produced 99% of the internal energy demand (for only one day) with renewable energy, while Portugal satisfied the 100% for four consecutive days (Armaroli et al., 2017, p.169). Even if the global share from renewable energy is still limited, as pointed out in figure 2.3, the so-called energy transition has begun (Leach, 1992).

Renewable energy

Exploiting wind to produce energy is one of the oldest technology. Since the Middle Ages, windmills have been exploited to support the human activities. Despite its long history, only in the last two decades wind power generators started to be widely used all around the world. Figure 2.6 shows the energy generation from 1965 to 2019 for different sources. Wind energy generation (blue line) started to grow only at the beginning of the new century (in 2000, was close to zero, less than 30 TWh) and, in less than twenty years it overpassed solar, geo, and biomass energy production. In 2019, it reached a global production of 1430 TWh, almost doubling both solar and geothermal energy production (BP, 2020).

Such an incredible result needs a few words about the technology. Wind turbines basically produce energy by electromagnetic induction, i.e. by exploiting the Faraday-Neumann law (Sadiku, 2007). Focus 2.3 briefly explains the physical principles.

Focus 2.3 — Fundamental of electromagnetism. The Faraday-Neumann law is a fundamental law of electromagnetism which defines that a variation in the magnetic flux $d\Phi_{\mathbf{B}}$ over time can generate an electromotive force into a conductor according

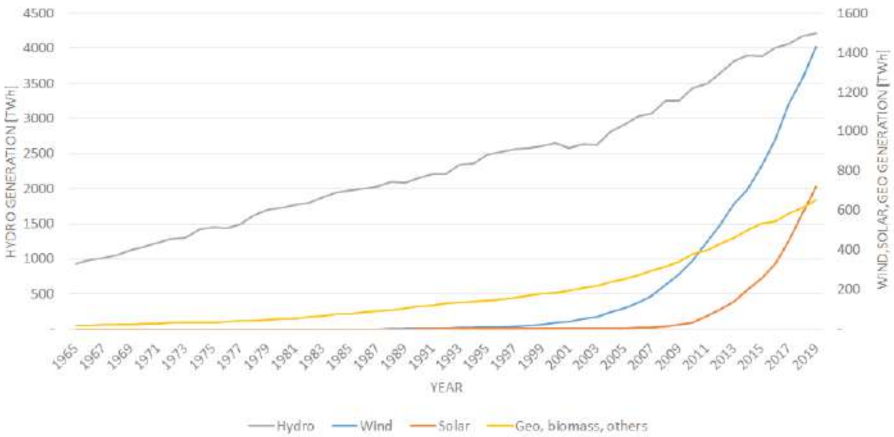


Figure 2.6: World renewable energy generation per different sources. Data source: (BP, 2020)

to:

$$\mathscr{E} = \frac{d\Phi_\mathbf{B}}{dt}$$

where $\Phi_\mathbf{B}$ is the magnetic flux, and $\mathscr{E}$ is the electromotive force. Together with the Ampere's law which links the magnetic field generated by an electric current to the electric current itself, the Faraday law is known since the XIX century and is commonly exploited in every transformer or electrical motor. The Ampere's law in mathematical terms is expressed as:

$$\oint_{\partial S} \mathbf{B} d\mathbf{r} = \mu_0 \sum_i I_i = \mu_0 I$$

where ∂S is a closed path around the currents, μ_0 is the magnetic permeability in vacuum, and I_i is the i-th current passing through the closed path.

Basically, a wind generator exploits the kinetic energy of the wind to move the wind turbine blades. Some magnets, due to the movement, generate a variable magnetic field which induce an electric current into the surrounding coil. ■

Avoiding too many technical details, to build wind generators proper zones are necessary. In general, for a wind turbines a constant wind, with an average optimal speed of $7 m/s$ at an height from ground of 80 meters, is needed. It has been evaluated that, the proper lands with these characteristics may generate about 70 TW, more than the total energy demand globally. The opportunity for a quick energy transition is undoubted if, furthermore, the time of construction of new wind generators is taken into account. For instance, a new wind power plant of 10 MW may be realized in less than two months. (Armaroli et al., 2017, p.172-174)

Moreover, within the energy transition several other energy technologies also play an important role. In the past century, the most exploited renewable energy production system has been the hydroelectric energy, as clearly shown in figure 2.6. The hydroelectric energy plants were the first ones to be developed and adopted worldwide and the total energy production is constantly increasing, from the annual 1000 TWh in 1965 up to the current production of more than 4000 TWh in 2019. Thus, till now the most part of renewable energy is attributable to hydroelectric energy. Despite its noteworthy contribution in the past decades, hydroelectricity caused many social and ecological problems due to the construction of huge dam (Barrow, 1988; Lin et al., 2017), which may affect local population, or even change local ecosystem and climate (Armaroli et al., 2017, p.179). For instance, some projects such as the Three Gorges Dam (TGD) on the Yangtze basin (K. Li et al., 2013) or the Italian Vajont dam (Barla et al., 2013) highlighted the related environmental impacts (the TGD) and the social and safety risks (the Vajont dam), undermining the further scalability of the hydroelectricity. The former is a huge project in China which has affected three valleys, forcing more than one million of people to move, and generating environmental problem of rock erosion, water quality decline, and negative effect on fishery and biodiversity (134 species have been fragmented and migration routes for 35 fishes have been blocked) (K. Li et al., 2013; Yang et al., 2007). The latter, instead, was an ecological and social disaster due to a landslide that fell into the artificial lake. The landslide caused a flood in the valley below, killing more than 2000 persons (Barla et al., 2013). Less dangerous, in

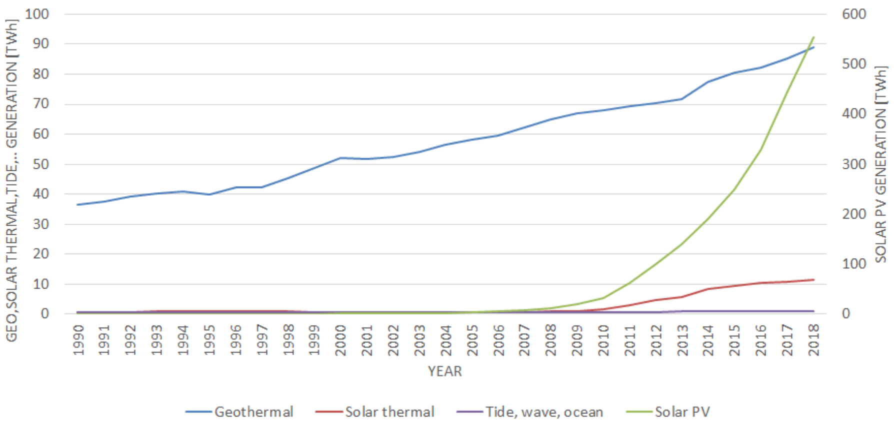


Figure 2.7: World renewable energy generation per different sources. Focus on solar and minor technologies. Data source: (IEA, 2020a)

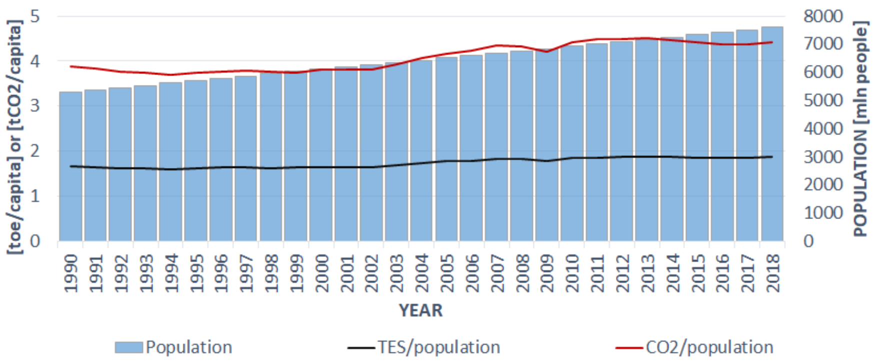
terms of ecological and social risk, is the most debated technology, the solar energy. The energy from sun, in particular, is the unique net input flow of energy on Earth, as discussed by many earlier environmental economists (Boulding, 1966; Daly, 1974; Goran Wall et al., 1986). Despite the great expectation in the past decades, looking at the evolution of the global energy generation (figure 2.6), the contribution of all the solar technologies is neither neglibible (in 2019, more than 2000 TWh has been produced) nor satisfactory as expected. Widely spread almost ten years after the initial adoption of wind energy generators, the exponential growth is emerging but the effective share on global production is still low. The solar energy is mainly used to heat water (solar thermal) or to produce electricity (solar photovoltaic). The solar thermal consists of two main types of panels, plate collectors, generally used for low temperature domestic hot water, and solar thermal-electric plants, for medium-high temperature heat or electricity generation (IEA, 2020b). Solar thermal plate collectors energy production is clearly underestimated, as declared by the IEA (2020b, p.49) itself, due to the difficulty to map and monitor plants for private dwelling. Solar-thermal-electric plants, instead, include different technologies, mainly concentrated solar power (CSP) (De Laquil et al., 1993).

Figure 2.7 shows the global energy production from 1990 to 2018, according to the data published by IEA (2020a). The solar photovoltaic technologies, starting from 2010, have exponentially increased their global production, even if not yet comparable with wind and hydro energy. On the contrary, solar thermal energy production linearly increased but only reached 10TWh globally in 2018 (vs the 554TWh of the solar PV), remaining a secondary source of energy. Finally, geothermal energy production has constantly increased since 1990, reaching almost 90TWh globally, while newest technologies, as the exploitation of tide, wave, or ocean current, are still at its early stage.

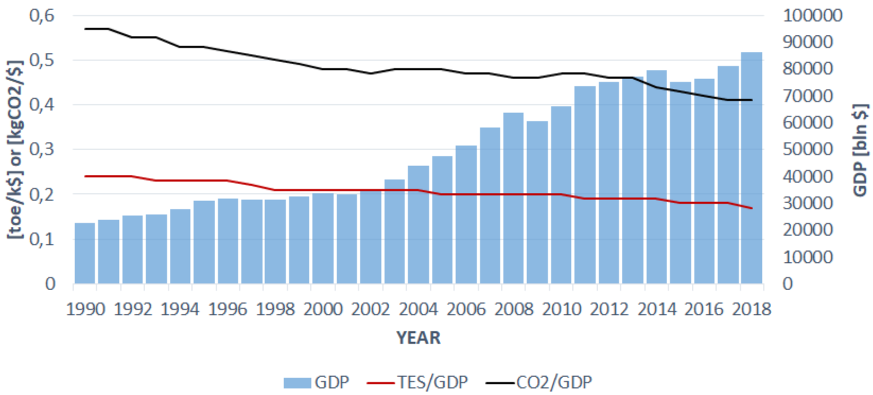
On top of these considerations on energy production technologies and their development in the past years, what is the aim to produce always more and more energy? Why is the global production, although all the efforts to reduce the consumption by increasing the energy efficiency of houses or industrial processes, constantly growing? Is it necessary for our society such a huge amount of energy?

As discussed by Rovers (2019) and presented in chapter 1, firstly, all fundamental physiological needs of every person in the world should be satisfied in order to live in the so-called *safe and just space* (Raworth, 2017). Thus, as the world population continues to grow, the energy demand will continue to grow. Secondly, the development of the developing countries is causing an extraordinary increase in products and services request, as the GDP is increasing. Figure 2.8 exhibits the world TES, expressed in tons of oil equivalent, and the total CO_2 emissions (in tons, or kg, of CO_2) versus the world population (fig. 2.8a) and the GDP (fig. 2.8b). Graph 2.8a highlights how the world energy supply, and relative CO_2 emissions, slightly increase as the population increases. The TES/population, and TES/CO2 ratio increased from 1.66 and 3.88 in 1990 to 1.88 and 4.42 in 2018, respectively, showing how total energy supply per capita remained almost constant during 30 years. On the contrary, the graph 2.8b points out how the TES/GDP and CO2/GDP decreased in the same period. This trend may be read as an average global increase of wealth although the necessity of energy per capita almost remains constant. By the way, for the sake of clarity, the inversely proportional trend is not a positive result *per se*. Indeed, for instance, the global GDP does not take into account inequality among population, as the GINI index does (Lerman et al., 1984).

Thus, what is the physical and real relation between energy and the increase of GDP, i.e., in other terms, products and services demand? In general terms, each product can be evaluated, despite all available environmental indicators, through the *embodied energy* necessary to produce it (Costanza, 1980; G. P. Hammond et al., 2008)



(a) TES vs population



(b) TES vs GDP

Figure 2.8: Total energy Supply and CO_2 emissions vs population and GDP. Data source: (IEA, 2020a) and (World Bank, 2020a; World Bank, 2020b)

2.3 Embodied energy

The idea of considering the available energy as the real constraint for human activities is not new at all. This constraint was known in physics since the XIX century and traced back to 1886. With the words of Boltzmann, *"life is primarily a struggle for available energy"* (Costanza, 1980). After 50 years, the available energy concept emerged also in economics. *"If we have available energy, we may maintain life and produce every material requisite necessary. That is why the flow of energy should be the primary concern of economics"* Soddy (1933, p.56) stated in his book *Wealth, virtual wealth and debt: the solution of the economic paradox* in 1933. In the Eighties, the embodied energy, in economics, has been later defined as (Costanza, 1980):

Definition 2.3.1 — Embodied energy. The total (direct and indirect) energy required for the production of economic or environmental goods and services.

The embodied energy (EE) of a product, or service is highly dependent on the used methodology, or on the boundary conditions. Regardless of the methodology used, generally it is a useful indicator to evaluate how much the life cycle of a product/service is energy intensive and thus how much the production impacts on global energy sources. Depending on the boundary conditions, it measures all energy requirements needed for the extraction of raw materials, the transport of them, the use or the End of Life (EoL). A few examples may help the reader to visualize the order of magnitude for certain common products and materials. For instance, to produce a ton of paper, an energy amount of about 0.8 toe is needed, for a ton of aluminium 3 toe, while for titanium about 20 toe. To produce a car, on average, 3.0 toe/t are needed, while for a single desktop computer about 0.140 toe (Armaroli et al., 2017, p.47). 1 toe is equal to 11630kWh. Thus, to produce a desktop computer 1628 kWh are needed, more than all the energy consumption of a person during a year (about 1100 kWh) (Rovers, 2019, pages 299–303).

With respect to energy production technologies, it is fundamental to quantify the embodied energy of a new wind or solar plant. Ortegon et al. (2013) assessed the embodied energy of wind turbines by analysing each component and material in order to prepare and evaluate end-of-service life of wind turbine strategies. According to their study, the total embodied energy for a 2MW wind turbine is approximately 9.5 TJ and the majority of embodied energy has been accounted to lie in the tower, blades, gearbox. Precise data are reported in table 2.4.

Table 2.4: Embodied energy and carbon for a 2MW wind turbine. Adapted from Ortegon et al. (2013).

Component	**Embodied Energy**		**Embodied Carbon**	
	GJ	%	tCO_2	%
Tower	4949.659	52	385.757	54
Nacelle	72.680	0.8	5.563	0.8
Hub	469.843	5	36.603	5.1
Blades	2078.037	21.8	147.323	20.7
Nose-cone	38.310	0.4	2.104	0.3
Converter	223.270	2.3	14.958	2.1
Generator	308.393	3.2	20.332	2.9
Gearbox	634.368	6.7	47.133	6.6
Bed frame	574.613	6	39.131	5.5
Main shaft	180.030	2	14.025	2
Total	9529.202	100	712.927	100

2.3.1 Energy return on investment

The purpose of understanding the embodied energy is twofold. First, it can be used to plan end of life strategies, and, second, it may be used to evaluate the so-called EROI (energy return on investment). According to Hall, J. G. Lambert, et al. (2014), it is defined as

> **Definition 2.3.2 — EROI.** A means of measuring the quality of various fuels, or power plants, by calculating the ratio between the energy delivered by a particular fuel, or power plant, to society and the energy invested in the capture and delivery of this energy.

and, according to J. G. Lambert et al. (2014), is expressed as

$$EROI = \frac{ER}{EI} = \frac{\text{energy returned to society}}{\text{energy invested to get that energy}} \tag{2.5}$$

Similarly, according to Hall, J. G. Lambert, et al. (2014), the EROI is defined as $EROI = {}^{E_{delivered}}/_{E_{required}}$, where $E_{delivered}$ is the total energy delivered to the final consumer, and $E_{required}$ is the necessary energy to deliver the corresponding energy to the final consumer. With this definition, an $EROI < 1$ represents an energy sink, i.e. an energy storage system instead of an energy production system. For $EROI > 1$, instead, the higher the ratio, the better the performance of such technology is. For instance, 1GJ with an EROI 50:1 means that 0.02GJ of energy are required to produce 1GJ, while to produce 1GJ with an EROI 10:1 about the 10% of the output (0.1GJ) is needed. The EROI primarily depends on the adopted methodology and on the considered boundary conditions. Indeed, the denominator of Eq. 2.5 varies if only the extraction of fuels (for fossil fuel for instance) is considered, or if also the transportation, infrastructure maintenance, and the end of life are taken into account (Hall, Balogh, et al., 2009; Murphy et al., 2011). According to (Hall, Balogh, et al., 2009), four different EROI may be established:

1. $EROI_{ST}$: in the standard EROI formulation the required energy $E_{required}$ includes the direct and indirect energy to make the "fuel" used on site but the energy necessary for labor and financial services, for instance, is not taken into account
2. $EROI_{POU}$: the point-of-use EROI also includes refining (for oil for instance) and the transportation to the final user.
3. $EROI_{EXT}$: the extended EROI adds the energy required also to use the energy.
4. $EROI_{SOC}$: finally, the societal EROI should include all energy requirement to use the analysed energy for the society.

For instance, according to Hall, Balogh, et al. (2009) estimation, each 100 MJ of oil, 10 MJ are lost during extraction (standard EROI), 10 MJ are used and lost in the refineries, further 17MJ ends as other oil products and 3MJ are used as fuel for transportation (point-of-use EROI). Finally, a last 24 MJ are lost in maintaining the required infrastructure (extended EROI) delivering about the 36% of the initial energy content. Societal EROI is still difficult to assess and is highly speculative (J. G. Lambert et al., 2014). Typical EROI values are reported in figure 2.9 for non-renewable (gray bars) and renewable (green bars) energy sources (Hall, Balogh, et al., 2009). The best performing energy source, as far as now, remains the hydroelectric power with an average EROI of 94.

The renewable energy sources, avoiding ethanol and diesel from biomass, currently, achieved an average EROI comparable with fossil fuel (except for coal) since, as fossil fuel reserves are exploited, the required energy to obtain an equivalent amount of fuel at the point of use is increasing due to the difficulty to reach existing deposits. As already noticed in terms of global production, the most promising renewable energy source is the wind energy, with the highest average EROI (avoiding hydroelectric power as discussed previously for its related environmental problems).

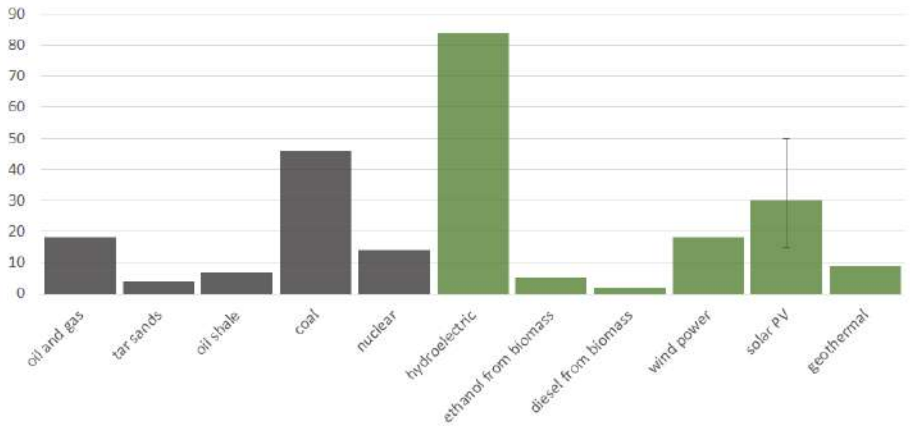


Figure 2.9: Average energy return on investment (EROI). Common non-renewable (gray bars) and renewable (green bars) energy sources are represented in different colors. Adapted from Hall, Balogh, et al. (2009). Due to recent improvement, EROI for solar PV refers to a more recent study (Zhou et al., 2018). The maximum EROI for solar PV may range between 15 and 30 for crystalline silicon panels and between ~ 15 and ~ 50 for thin film panels.

In general, the EROI values are highly dependent on the current technologies, for renewable energy sources, and on available reserves, for non-renewable energy sources. For instance, in US oil EROI in 1960 was less than 20:1, in the seventies rose to 30:1 and, then, dropped down up to 10:1 in 2010 (Hall, Balogh, et al., 2009). Global oil and gas EROI, instead, from the nineties decreased from 35 in 1999 to 18 in 2006 (Gagnon et al., 2009). Up-to-date estimations on solar photovoltaic EROI established a lower and upper bounds of 5 and 30 respectively (Pickard, 2017).

EROI and societal needs

What is the link between the EROI and the developing of a society? What is the minimum energy return on investment value for a developed country? As qualitatively described by Rifkin (2015) in his book *The zero marginal cost society* the drivers of the past, and the current, industrial revolutions were new technologies within the energy - transportation - communication matrix. Indeed, the extreme importance of the energy availability to support the well-being of people in a society has been recognized by both academics and policy-makers (J. G. Lambert et al., 2014), as clearly pointed out by the dedicated SDG 7, “affordable and clean energy” (UN, 2020). Since energy is necessary to produce any kind of good or service, energy availability, its production efficiency, or the quality of the energy have direct effect on the wealth of a country and on citizenships’ lifestyle. The development of a society, thus, may be measured through and associated with the energy availability. For instance, White (2016) pointed out the need of surplus of energy to fully develop progress in art and culture. EROI is one of the possible indicator of both availability and production efficiency/quality. EROI, GDP and social well-being are linked through a simple causal chain - $EROI \rightarrow GDP \rightarrow$ social well-being - as proposed by J. G. Lambert et al. (2014). They find strong correlations among the EROI of a country, i.e. the weighted EROI average over all the energy sources of a country, and the Human Development Index (HDI), the Gender Inequality Index (GII) and they developed the Lambert Energy Index (LEI), a composite index based on the geometric mean of the EROI, the energy per capita and the Gini-index. Their findings highlighted how the higher the EROI, energy per capita, or the LEI, the higher the HDI, and GDP, is for a country. The trend of the HDI was not linear but logarithmic. Thus, above a certain amount of energy availability (200 GJ per capita per year) no further improvement in the HDI occurred and a saturation point was found. Their findings supported the idea of a energetic needs hierarchy, similarly to the Maslow (1943) pyramid for human needs, or the Rovers (2019) foundation of physiological needs. Figure 2.10 shows the energetic needs pyramid, where at the foundation, first there are the basic functions - extract, refine and transport energy, and grow food - for a human society, and, then, there are the social functions associated to an increasing well-being (J. G. Lambert et al., 2014). Although the top of the pyramid cannot be directly measured in terms of energy availability or EROI, the underlying concept is that surplus of energy, once fulfilled the basic human needs, as shelter and food, then, may be used to develop education, healthcare, arts and culture.

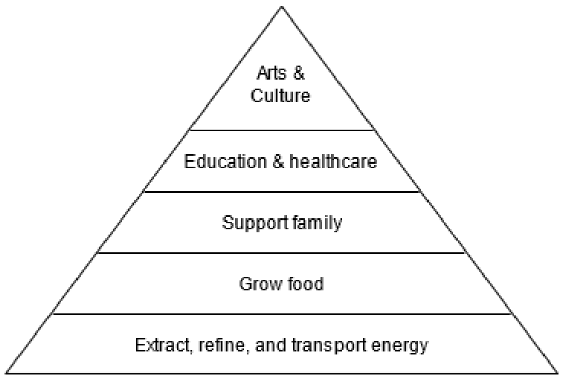


Figure 2.10: Energetic needs pyramid. It shows the minimum EROI necessary to fulfil the hierarchical societal functions. The foundation from extract, refine and transport energy up to grow food are published data. Adapted from J. G. Lambert et al. (2014).

On top of this discussion, as previously discussed in chapter 1 and as pointed out brilliantly by D. H. Meadows, D. Meadows, et al. (2018), the used material should be the ultimate constraint for a sustainable management of the Earth. Indeed, although theoretically, as stated in the Thirties by Soddy (1933), if we have enough energy, we may recover and maintain every material, in the real world this is not properly true due to economic prices, scarcity of materials and geopolitical issues, or simply due to the unavailability of proper technologies and processes. Indeed, for instance, according to Ortegon et al. (2013), a wind turbine is composed by several materials such as steel, aluminium, fiberglass, resin, silica, copper, concrete, and the so-called rare earth (REE). With respect to the embodied energy, the majority derives from the steel used in the tower (the 98% of material used in the tower is made of steel) and from fiber glass used in the blades (78% of mass of blades). Although as shown by Hall, Balogh, et al. (2009) the EROI of wind turbine is 18, i.e. a very profitable one both in economic and environmental terms, other issues should be taken into account, mainly regarding the REE (dysprosium, praesodymium, and neodymium) used in the permanent magnets for the generators. Indeed, the global production of such materials is dominated by China and price volatility, and material supply risk may occur due to geopolitical instability (Ortegon et al., 2013). Finally, it is noteworthy to introduce the Jevons paradox (Alcott et al., 2012). It points out the situation when an increase in efficiency, due to technological improvement or new policies, for the production of a certain material (or source of energy) reduces the required material to produce the same amount of goods and commodities but this improvement provokes an increase in the demand of that good, resulting in a total increase in the exploitation of the used materials. The Jevons paradox, also known as *rebound effect*, is particularly crucial in the current energy transition towards renewable energy, as pointed out by the IEA in its latest report on *The Role of Critical Materials in Clean Energy Transitions* (IEA, 2021). Indeed, the improvement in efficiency for the renewable energy is provoking an exponential increasing demand for renewable energy (with a consequent exponential increasing in raw materials demand) and it could induce an increase in household consumption (Greening et al., 2000).

Thus, after this brief introduction on energy availability, production technologies, and embodied energy, in next chapter, the physical material constraint will be presented.

3. Materials

Materials, from fossil fuels to minerals, are essential to human society and its development. This is clear and undoubted. Since the prehistory, mineral resources, like water, energy, and food sources, have been at the core of human development, supporting the basic functions any human being on Earth needs to, first, survive, and then, thrive.

The first stone tools appeared in the East African region between 2.5-1.5 million years ago, in the late Pliocene/Lower Pleistocene (Bunn et al., 1980), although the debate on the date when the first stone tool was created is still open. According to Semaw et al. (2003), it dates back to about 2.6 million years from the region of the Afars in Ethiopia, and it opened the Stone Age. These rudimentary tools allowed to hunt and, consequently eat, better and more efficiently. The first source of energy, the use of fire, instead, appeared after more than one million years ago; generally, the control of fire traces back to 0.5 millions years B.P. (before present), in the Middle Pleistocene, and it is attributed to the Homo Erectus (James et al., 1989). Other academics, instead, trace back the discovery to 1.4-1.7 million years B.P., in Kenya (J. A. Gowlett et al., 1981) or in China (Jia, 1985). The first metal mine probably was the Lyon Cave (40.000 years ago), exploited to produce ritual paintings from an iron oxide (Christmann, 2016), even if the very first beginning of metals manipulation dates back to 9000 years B.P.. In the region among Turkey, Iraq and Iran, indeed, copper was used to create small objects such as pins. Officially, the Chalcolithic, i.e. the Copper Age, began around the 7000 B.P. in the area between Eastern Europe (Radivojević et al., 2010), and Iran (Tylecote, 1992). Recently, the first copper mine has been discovered in Belovode in

Eastern Serbia (Radivojević et al., 2010). One of the first lead objects, instead, was found in the northern Negev desert, in a cave in Israel, and traces back to the Late Chalcolithic period (around 5000 B.P.) (Yahalom-Mack et al., 2015). Thus, the beginning of the metallurgy, and the exploitation of raw materials, is quite recent if compared with the human history. Since then, the exploitation of metals and other raw materials constantly increased moving from the Bronze Age, generally attributed to the Mesopotamia area (the Near East zone) between 4200 and 3000 B.P. (Childe, 1930; Dickinson et al., 1994), to the Iron Age. According to the *three-age* (stone, bronze, and iron) classification proposed by Christian Thomsen (Harding, 2011), officially formulated between 1870 and 1880, (Wells, 2011), the European Iron Age started around the 3000 B.P.. At the same time, smelting technology improvement allowed to use and exploit several other metals and elements for various applications, from pottery to the forge of weapons, from cosmetics to agriculture tools. For instance, the drachme of Athens were made in argent, while the Romans used mercury for cosmetics (Christmann, 2016). However, the annual production and consumption of metals has been relatively low up to the XVIII and XIX century and the first industrial revolution. For instance, copper total production, during Roman period, has been estimated by analysing the concentration within Greenland ice to be around 15.000 metric tons per year in its peak about 2000 years ago. Then, the production dropped down to 2000 metric tons until the VIII century, rising again during the Middle Ages (Hong et al., 1996).

Mining techniques were strongly developed after the Middle Ages and metals and minerals extraction rapidly increased from the XVII century, also thanks to the use of the gunpowder as explosive (firstly used in 1627 in Slovakia), and in 1735 the first School of Mines was inaugurated. Finally, modern mining techniques, were introduced during and after the first industrial revolution. The discoveries of the steam engine of Newcomen and Watt in 1769, the introduction of the steel industry thanks to Bessemer in 1857, the dynamite of the Alfred Nobel in 1867, and the aluminium industry deeply improved the mining sector in the XIX century (Christmann, 2016). Thus, since the eighteenth century the exploitation of the materials deposits started an exponential growth, rapidly becoming one of the most polluting sectors in the world.

The linear consumption of raw materials is not sustainable anymore. Nowadays, in 2019, the European Union with 27 countries (EU27) *Domestic Material Consumption* (DMC) reach the huge amount of 6,325,357.613 thousand tonnes. The DMC represents the amount of materials used by a country, i.e. the net material consumption. It is directly equivalent to the *Direct Material Input* (DMI) minus the *Physical Exports* (EXP), based on the following expression

$$DMC = DMI - EXP \tag{3.1}$$

The DMI is a measure of the input of material into a national, or regional, economy. It reflects both the Domestic Extraction (DE) and the Import (IMP), according to

$$DMI = DE + IMP \tag{3.2}$$

By considering only the fossil fuels, in EU27 the DMC reached the impressive amount of 1,270,606.995 thousands tonnes, while the total DMC in 2019 was 6,325,327.613 thousands tonnes (Eurostat, 2020a). This huge amount is equivalent to build more than

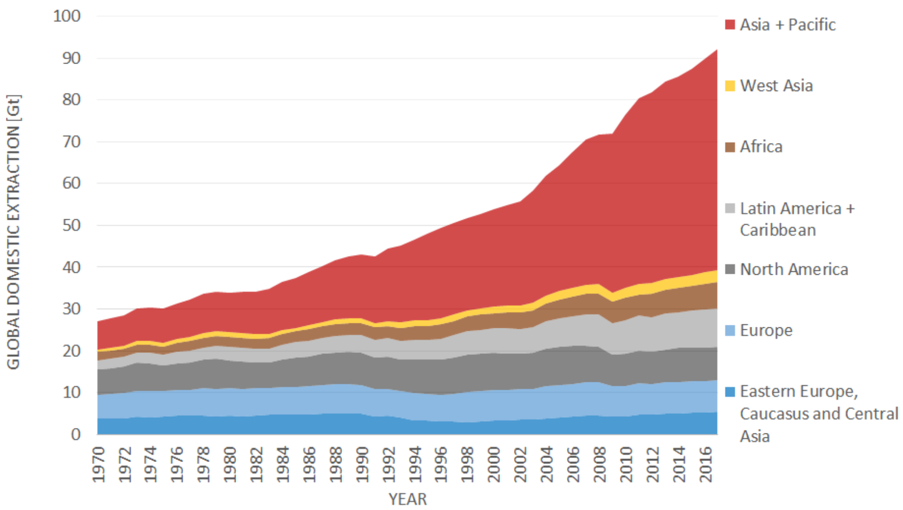


Figure 3.1: Absolute global Domestic Extraction (DE) per area of origin. Data source: UNEP (2020)

1000 Cheops Great Pyramid (about 2.7 millions blocks of 2.3 tons each) each year (Ghoussayni et al., 2020; Rasmussen, 2020; Romer, 2007).

Although domestic material consumption and extraction of the European Union remained almost constant in the past decades, thanks to technology improvement, and to the slower growth of population, the same trend is not true at global level, due to the fast development of several developing countries. Similarly to the total energy supply trend (shown in fig. 2.2), at global scale the BRICS countries (Brazil, Russia, India, China, and South Africa), i.e. the fastest emerging economies in the World, are leading the domestic extraction and consumption. Figure 3.1 shows the global domestic extraction, expressed in Gt (billions of tons), per geographic area (Asia + Pacific, West Asia, Africa, Latin America + Caribbean, North America, Europe, and Eastern Europe). Domestic Extraction includes fossil fuels, raw materials (metal ores and non-metallic minerals), as well as biomass and renewable materials extraction such as crops and woods (UNEP, 2020). Worldwide the DE is steadily growing since the seventies, overpassing 90Gt in 2017 (about 15000 Cheops Great Pyramids of material). From the Ninenties, the materials extraction growth has been totally dominated by the Asia + Pacific area, which from 1990 increased by a +246% (+686% with respect to the 1970). On the contrary, Europe and North America domestic extraction has been almost constant in the period 1990-2017, +10% and +2%, while from 1970 it increased of +34% and +30% respectively.

Similar findings and trends emerged by looking the global domestic extraction share (%) per geographic area. Figure 3.2 highlights the percentage of domestic extraction for each area from 1970 to 2017. The Asia + Pacific area increased its share from an initial

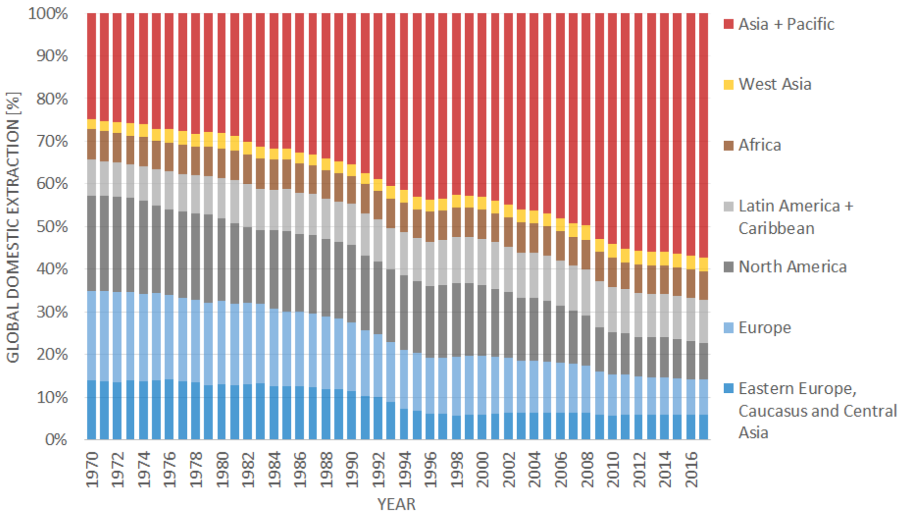


Figure 3.2: Share of global Domestic Extraction (DE) per area of origin. Data source: UNEP (2020)

25% in 1970, to 35% in 1990, passing the 50% of global extraction in 2008 and reaching the 57% of the global domestic extraction in 2017. On the contrary, the European Union (Europe + Eastern Europe) and North America decreased their share from 35% and 22% in 1970 to 14% and 9% respectively in 2017. The rest of the world, West Asia, Africa, and Latin America, instead, maintained their global share almost constant, 2%, 7% and 8% in 1970, 3%, 7% and 10% in 2017.

Finally, figure 3.3 reports the global trade exchange share per geographic area in 2013. Again, material flow exchanges are dominated by the Asia + Pacific area both in input and output with more than the 50% of global exchanges occurred within the Asia + Pacific area itself. Comparing input and output exchanges, 54% and 55% respectively, the Asia + Pacific area appears almost self-sufficient, balancing input and output flows. On the contrary, Europe and North America input (16% and 13%) are higher than output (9% and 11%), although most of the exchanges occurred within the continent itself. For all the other regions, output exchanges are greater than input. Two main behaviours emerge. Africa, Eastern Europe and Latin America geographic areas almost fulfill the trades by internal exchanges, and, in addition, they have noteworthy trades with all the other areas. West Asia economy, instead, is completely dependent from all the other countries. Indeed, almost all the outputs end in other regions, and almost all inputs derive from other regions.

The presented overview at global level leads to a few relevant considerations, in terms of materials extraction, that need to be discussed. First, although environmental economics and the discussion on the limits to growth emerged more than fifty years ago, not enough has yet been done and the global trends show a worrying picture.

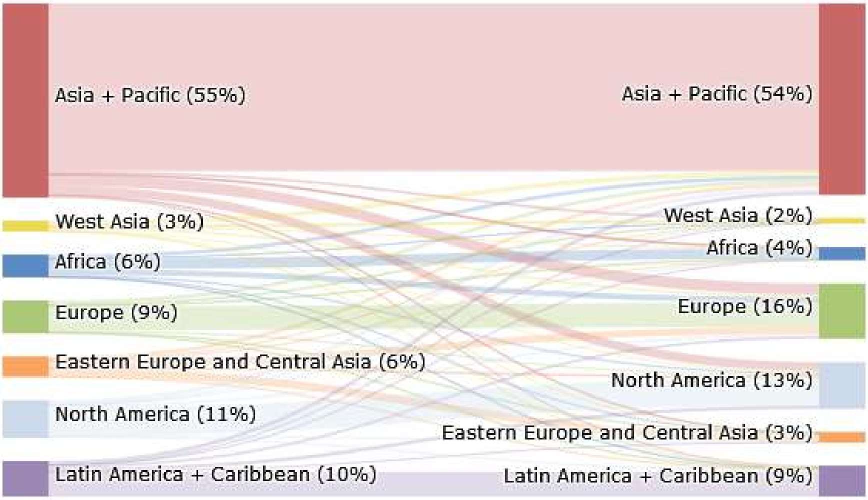


Figure 3.3: Global trade exchanges in 2013 per global region. Source: WU Vienna (2020)

Although Europe and North America, in last decades, drastically improved the efficiency of many industrial processes, increased the recycling rate and introduced even more stringent laws and regulations in order to reduce waste generation, the huge effort has not been enough to offset and balance the development of the Asia continent, mainly due to China and India fast industrial and social improvement, and, consequently, their materials demand. Despite the huge materials demand of the Asia region, as well as the energy demand as discussed in the previous chapter, counter intuitively, China has been one of the first country in the world to adopt, first, pilot projects, and, then, regional policies to implement a circular economy approach with the aim to reduce the high dependency from material extraction from the environment (Su et al., 2013). Heming Wang et al. (2020) analysed China's economy in the past two decades and they estimated that circularity improved to 5.8% in 2015, from an initial 2.7% in 1995, and the recycling rate increased by almost 10% (from 7% to 17%). In the same period, the total domestic extraction of China increased from 10,347.813 Gt to 30,844.488 Gt, a growth of the 198% (WU Vienna, 2020). It is clear that the effort put in recovering materials cannot offset the economic growth and its related materials demand. Second, if the Nineties and the first decade of the new century have been dominated by the fast development of the Chinese and the Indian economy, the African economy has still to be developed, and prediction estimates a constant growth in next decades, moving GDP from current 2000 billions $ to about 10000 billions $ in 2050 (+400%) (AFDB, 2011). Third, figure 3.3 underlies the high interdependency of world material trades and exchanges and how the economies of certain geographical areas, especially Europe, North America, and West Asia, deeply depend on materials inputs. These trends disclosed potential geopolitical

Figure 3.4: Global domestic extraction per material type (% of total mass in tonnes). Data source: WU Vienna (2020).

risks, especially for rare raw materials necessary for strategic technologies and economic sectors, and, recently, it opened a lively debate on the criticality of materials (S. Bobba et al., 2020).

3.1 Resource depletion

From the previous general description on material extraction, one can properly and correctly question how is the total domestic extraction composed? What are the materials' streams considered in this huge number? Are all material flows equal, and do they need the same effort to be produced, disposed of, and recovered? What are the material flows most urgent, in terms of negative impacts, to consider? Obviously, each material is different from another in terms of environmental impacts, available reserves and geographical distribution, and of importance for society needs. Some materials can be easily substituted with other materials with similar properties, others not. Some materials derive from renewable stocks, others from finite deposits. Figure 3.4 shows the composition (percentage over the total amount expressed in tonnes) of the previously discussed global domestic extraction. The DE is composed by four main categories

(Eurostat, 2020b):

1. *Non-metallic minerals* refer to sand, gravel, limestone and fertiliser minerals;
2. *Metal ores* include all the materials extracted from mines in order to reach the desired metal. Thus, metal ores also consider mining by-products but do not take into account all material extracted and left on-site near the cave zone.
3. *Fossil fuels* consist of all non-renewable sources, from coal to oil, from natural gas to non-renewable industrial and municipal waste;
4. *Biomass* is the organic non-fossil material, such as wood pellets, wood waste, sugarcane, sewage sludge, animal waste or algae, used to produce biofuels, biomass feedstock and energy crops.

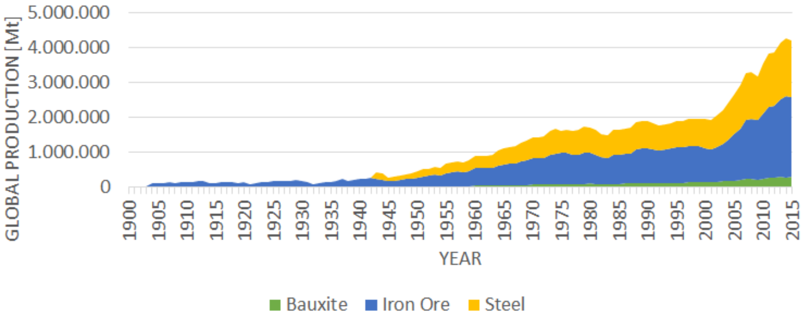
According to the data provided by UNEP (2020), the majority of global domestic extraction derives from non-metallic minerals (48%), mainly due to construction materials (46%) and only a minimal percentage derive from industry and agriculture (2%). Construction materials principally are composed by sand gravel and crushed rock for construction, limestone, and structural clays. Metal ores are split into ferrous ores (10%), mainly iron (4%), and all other metals (6%), mainly copper and gold. Fossil fuels account for the 17% on the global domestic extraction largely from coal (9%), split into coke, lignite, and other bituminous coal, petroleum (5%) and natural gas (3%). Finally, biomass represents the 26% over the total and is made of crops (10%) and crop residues (8%), grazed biomass and fodder crops (5%) and wood (3%).

As anticipated, materials stocks may be split into deposits (non-renewable stocks) and funds (renewable stocks); the only limits for funds are related to the regeneration rate, land space, and eventually to the environmental impacts of agriculture activities, while the extractions from deposits have to be managed wisely and each material waste is worthwhile, due to the lack of an infinite reserve. Obviously, some materials are quite common on the Earth crust, while others are not. Materials, such as the ones used for construction (sands, limestone, or clays), are abundant and the main issues are related to the environmental impacts due to the extraction, production, and transport of materials. On the contrary, metal ores and fossil fuels derive from geographically bounded mines and caves and supply shortage may occur in the near future due to political instability, when the extraction is dominated from a few countries, or simply to the limited amount present on Earth.

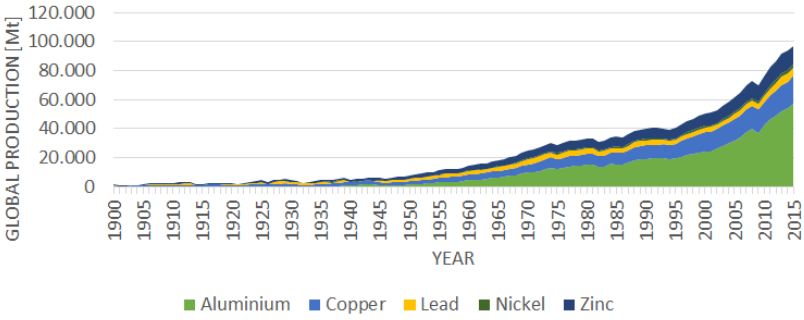
Global metals production

Figure 3.5 reports the global production of several metals expressed in million of tons. Metals global production constantly increased since the beginning of the XX century.

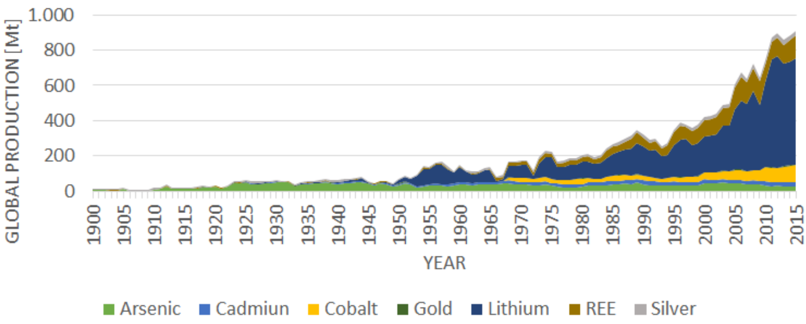
Until the world war II, global production was dominated by the ferrous ore extraction (figure 3.5a), i.e. iron ore, which in 1939 reached a global production of 200.000 Mt per year (fig. 3.5a). During the World War II, iron production was primarily used for the steel production. In 1943 steel production was 172.000 Mt, about the 75% of iron production. Steel, originally known from the XVI century, is an alloy of iron with a carbon content ranging from .2 to 1.5 percent to improve physical properties. However, the mass steel production started only during the XIX century thanks to Henry Bessemer, a British metallurgist, and the introduction of his *converter* and the so-called Bessemer process which allowed to produce large and cheap amount of steel simply injecting compressed



(a)



(b)



(c)

Figure 3.5: Metals global production from 1900 to 2015. Data source: (USGS, 2020)

air through the melted iron (Spoerl, 2004). After a drop in iron and steel production in the years after 1945, they both constantly increased until 1975, due to the high demand, first, in the post war period and, second, for the economic boom in Europe and North America. From 1975 and 2000 the production remains almost constant, while with the new millenium a sudden growth occurred up to 2015 because of the high Chinese and Indian demand. The same trend occurred for the aluminium, obtained from the bauxite, a sedimentary rock with a high percentage of aluminium.

Other non-ferrous metals such copper, lead, nickel, and zinc (figure 3.5b, slowly increased their global share from about the 1% with respect to iron ore extraction up to the 3%, reaching a total production of 2130, 1740, 122, and 1500 Mt per year in 1939. After the World War II their global production continued to grow but they remained secondary till now (around a 2%).

Other metals, such as arsenic, cadmium, cobalt, gold, lithium, rare earth (REE) and silver, are represented in figure 3.5c. Their production has always been much lower than ferrous ores and other metals used in infrastructure and transportation technologies. Arsenic production has remained almost constant from the 1920s until now - between 20 and 40 Mt - while cadmiun production rose only after the World War II from 5 Mt in 1945 to more than 20 Mt in 2015. Gold and silver production, due to their scarcity, remained quite low, about 3 and 25 Mt per year. While gold never experienced a significant increase in production, silver extraction constantly grew during the whole past century. Finally, cobalt, lithium and REE extraction emerged only from the Seventies, due to the introduction and large adoption of new technologies such as electric batteries, or more recently solar PV technologies. In 2015, they reached a global production of 97, 604, and 130 Mt respectively which is still growing.

Global reserves

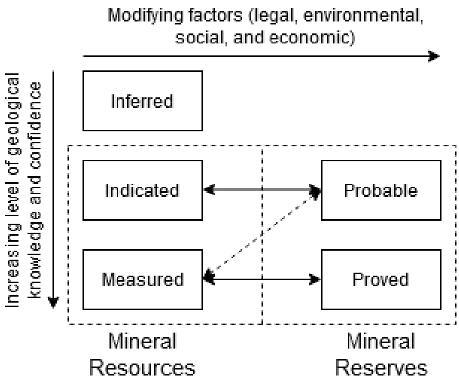


Figure 3.6: Resource and reserve classification. Adapted from CRIRSCO (2012).

The total amount of available raw resources globally is estimated yearly by the United States Geological Survey (USGS) (USGS, 2020). According to CRIRSCO (2012) available materials can be classified into two main categories:

- *mineral reserves* (proved or probable) are composed by economically mineable materials, taking into account several *modifying factors* like material dilution, metallurgical technology, material price, and other environmental, social or political factors;
- *mineral resources* (inferred, indicated, or measured) represent the known amount of material of reasonable economic interest for eventual extraction.

In other words, according to USGS (2020), reserves are the *"part of the reserve base which could be economically extracted or produced at the time of determination"*, where the reserve base is defined as the *"part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices"*. Figure 3.6 shows, schematically, the classification of inferred, indicated, and measured mineral resources, and probable and proved reserves. Reserves and resources are generally estimated according to the grade and the average concentration, in order to report only such deposits with a minimum grade (Jowitt et al., 2020).

Similarly to the discussion on fossil fuels, for each material a useful quantity to estimate, even if highly debated (Jowitt et al., 2020), is the reserves to production ratio. The ratio represents the depletion time, expressed in year, of the known and available reserves maintaining the same current production rate. Table 3.1 summarizes the R/P ratio for several common metals. Avoiding cadmiun, lithium, and rare earths, all the other metals and rocks reserves - bauxite, cobalt, copper, gold, lead, nickel, iron ore, silver and zinc - will last less than one hundred years (gold, lead, nickel, silver, and zinc less than 30 years). The reserve to production ratio is a limit result. Indeed, a better scenario figures out by considering the mineral *resources* instead of the reserves. In this case, the R/P ratio for the materials presented in table 3.1 is greater than one hundred years (except for nickel).

The R/P ratio should not be considered as a precise prediction on global resource depletion, but as a static snapshot of current situation. Indeed, it indicates how long current mines and caves will last with the current production. Nothing can be said about future new mineral reserves discoveries. For further detail, one can read the focus 3.1. Moreover, the R/P ratio is a rough estimation due to several approximations. In fact, many materials are obtained as by-products of other minerals and precise estimations do not exist. For instance, arsenic may be obtained from copper, gold, and lead and world reserves data are unavailable. Similarly, cadmium reserves data are not available but it can be estimated from zinc reserves (cadmium content within zinc ores is about 0.03%). Cobalt resources have been approximated to 25 Gt, but more than 120 Gt have been identified on the bottom of the oceans. Lead can be extracted as by-product within zinc, silver, or copper deposits, while silver from lead-zinc, copper, and gold mines (USGS, 2020). Copper resources are about 2.1 billion tons, but recently undiscovered copper resources have been estimated around 3.5 billion tons (K. M. Johnson et al., 2014)

As the R/P ratio is a rough indicator, detailed analyses and considerations on the depletion of materials should take into account several other factors, from an environmental impact point of view to social, political and legal aspects, which may affect the availability and the supply of certain materials. For this reason, recently Thomas E Graedel, Ermelina M Harper, et al. (2015) developed a precise methodology to assess

Table 3.1: World production and known mineral resources and reserves. Data source: USGS (2020)

Material	Production [Mt/year]	Resources [Mt]	R/P ratio [years]	Reserves [Mt]	R/P ratio [years]
Arsenic	33	-	-	-	-
Bauxite*	370	55000	149	30000	81
Cadmiun	25	57000	2280	7500	300
Cobalt	140	25000	179	7000	50
Copper*	20	2100	105	870	44
Gold	3,3	-	-	50	15
Lead*	4,5	2000	444	90	20
Lithium	77	80000	1039	17000	221
Nickel*	2,7	130	48	89	33
Iron Ore*	2500	800000	320	170000	68
REE	210	-	-	120000	571
Silver	27	-	-	560	21
Zinc*	13	1900	146	250	19

*values in Gt

the criticality of materials. In next section, the methodology and relevant findings will be briefly presented.

Focus 3.1 — The debate on resources peaks. In a recent article (Sept. 2020) titled “Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production”, published in the Communications Earth & Environment Journal, the debate on the limit of global reserves has been opened again. Jowitt et al. (2020) discussed the reserve-production ratio during the past sixty years (from 1957 to 2018) by analyzing the public data of the United States Geological Survey. In their article, they resurrected the debate about the wrong prediction of the Hubbert peak related to the fossil fuel (Hemmingsen, 2010; Priest, 2012), highlighting the linear trend of the metal reserve-production ratio, suggesting that other factors, i.e. environmental, social, and governance (ESG), will be the main risk in the near-future, rather than the large debated shortage in material supply (Gordon et al., 2006; Harald U Sverdrup et al., 2014; Harald Ulrik Sverdrup et al., 2019). As an example, to explain the failure of forecasting models, Figure 3.7 shows the true extension of a hypothetical mine, highlighting the unpredictability of available resources and reserves (even only considering the known ones). As a consequence, the data published yearly by the USGS about global reserves and discussed in this chapter cannot be considered as-is and are a poor guide to identify possible future resources peaks. Indeed, past analyses which considered materials reserves as fixed known stock are *inevitably inaccurate and pessimistic*, due to their probabilistic estimation approach (Jowitt et al., 2020). Findings show that, bulk and ferrous, and gold and silver reserve to production ratio trends are generally flat or decrease slightly. The same occurs for copper, lead, nickel, tin and zinc, pointing out that simple depletion models cannot satisfactory predict resources peaks. The linear trend of the reserve to production ratio, in particular, means that known global reserves increased at the same rate of the production. For instance, known iron ore reserves increased from 25,400 (in 1956) to 170,000 Mt (in 2018), with a growth of +570%. Similar trend in global reserves, although with a slighter increase, occurred for copper (from 145 to 830 Mt), nickel (from 40,440 to 89,000 kt), silver (from 155.5 to 560 kt), and gold (from 31,100 to 54,000 t), just to name a few. Finally, according to Jowitt et al. work, the reserve to production ratio, from 1987 to 2018, slightly decreased for antimony, bauxite, chromium, cobalt, iron ore, manganese, and rare earths, among others. On the contrary, phosphate, and lithium, increased their ratio, while all other metals had a constant ratio over time. This can be explained by several factors. Change in prices, increase in demand, the emergence of new technologies and mining techniques, indeed, motivate new investments of mining companies to seek for new reserves, or to start the exploitation also of the *mineral resources*, i.e. mines with a lower concentration, in order to satisfy the increase in demand. Shortage in mineral supply, thus, should focus more on ESG factors. For instance, the lower the ore concentrations, the higher the environmental impact or the energy used, and limitations in the exploitation could occur due to more stringent environmental laws and regulations. ESG factors are still under debate by scholars and decision-makers, and, nowadays, the unique indication we have to avoid future exploitation of the environment is the current global snapshot. ■

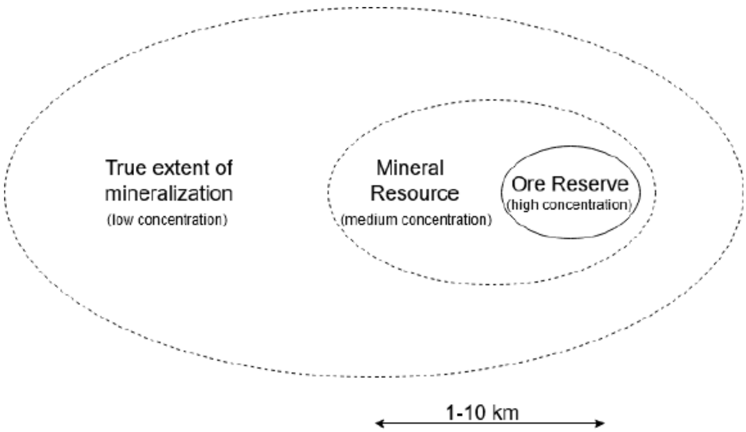


Figure 3.7: Representation of reserve and resource. True extent of mineralization. Adapted from Jowitt et al. (2020)

3.1.1 Critical raw materials

Following the previous past discussion about materials depletion and world production trends (Jowitt et al., 2020), in the short-medium term, the urgency is not related to the shortage of supply but to possible environmental, social or political risks which may affect global trades and exchanges. Although in the long-term (from a few decades to hundreds of years, not years) the depletion of fossil fuels and raw materials and the predictions of D. H. Meadows, D. Meadows, et al. (2018), and of other environmentalists, still remain the main issue to be solved for a thriving society, in the near-future, global materials production and supply should be treated by considering the criticality of materials. To this purpose, Thomas E Graedel, Barr, et al. (2012) proposed a "Methodology of metal criticality determination". The same approach can be applied to any raw material. The proposed methodology consists of three main factors:

1. *supply risk* (SR) represents the availability of a material;
2. *environmental implications* (EI) includes the environmental impact corresponding to the extraction, processing and transport of a material, i.e. from cradle-to-gate;
3. *vulnerability to supply restriction* (VSR) refers to the substitutability potential of a material with a similar one and its importance in the market, as well as corporate or national ability to innovate.

Each factor is computed by including different sub-indicators both for time-scale - short-medium (5-10 years) and long-term (decades) - and for organization size - corporation, national, global. Corporate and national indicators may be evaluated both in short-medium and long-term, while at the global scale only the long-term assessment is worthwhile. At corporation and national scale sub-indicators assess both material features (availability, geographical origin or geopolitical risks due to the country of origin) and corporate/national characteristics (dependence from a material, corporate/national ability to innovate, resistance to cost increase). At global scale, intuitively, some considerations, such as national geopolitical risks, are meaningless. Figure 3.8 shows the critilicality indicator at the global scale. It consists of the average of the three categories (SR, EI, and VSR); each category score is computed by weighting the corresponding sub-indicators, as shown in figure 3.8. The final criticality score, $||C||$, as well as each sub-indicator, ranges between 0 and 100, where 100 is the worst criticality score for a material. Further details and a brief discussion on the adopted criteria at global scale are provided into the focus 3.2.

Focus 3.2 — Criticality Determination. Thomas E Graedel, Barr, et al. developed a methodology to assess the criticality of materials in order to take into account all relevant criteria (technology improvement, price trend, ability to innovate, geopolitical risks) and not only the material availability. The criticality score is defined by weighting equally the three main factors - *supply risks, environmental implications*, and *vulnerability to supply restriction* - according to:

$$||C|| = \frac{\sqrt{SR^2 + EI^2 + VSR^2}}{\sqrt{3}} \tag{3.3}$$

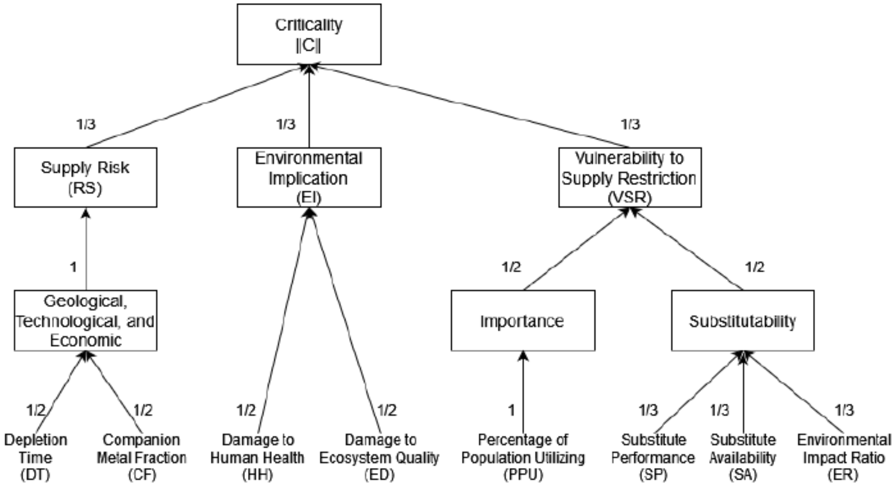


Figure 3.8: Representation of the material criticality indicator at global scale. Source: Thomas E Graedel, Barr, et al. (2012)

where SR is the supply risk, EI the environmental implications, and VSR the vulnerability.

At the global scale, the supply risk SR is simply evaluated in terms of global material availability, due to the unpredictability of technology evolution and other sub-national effects, according to $SR = {}^{(DT_{Transformed}+CF)}/_{2}$, where $DT_{Transormed} = 100 - 0.2DT - 0.008DT^2$ represents the normalized (between 0 and 100) depletion time DT and CF the companion metal fraction. The CF represents the percentage of a metal recovered as a byproduct (i.e. a companion) of a "host metal", while the depletion time is equal to $DT = t_f - t_0$, where t_f is the time (year) when the global reserves will be exhausted and t_0 is the current year and are calculated as a function of the current global production according to:

$$R_{t_f} = R_{t_0} - \int_{t_0}^{t_f} \rho\,(t)\,dt = 0 \tag{3.4}$$

R_{t_f} and R_{t_0} represent respectively the reserves at time t_0 and t_f, while $\rho\,(t)$ is the global production and it can be computed as a function of material production scraps, recycling rates, and the average lifetime of products where the material is used in.

The environmental implications EI consider material toxicity, use of energy, water footprint and emissions to land, air or water, just to name a few. EI is computed by evaluating two environmental indicators, i.e. the damage to human health (HH) and to ecosystem quality (ED), through a Life Cycle Assessment, from cradle to gate, according to the ReCiPe end-point method with *hierarchist* weighting (Huijbregts et al., 2017) and, subsequently normalized between 0 and 100.

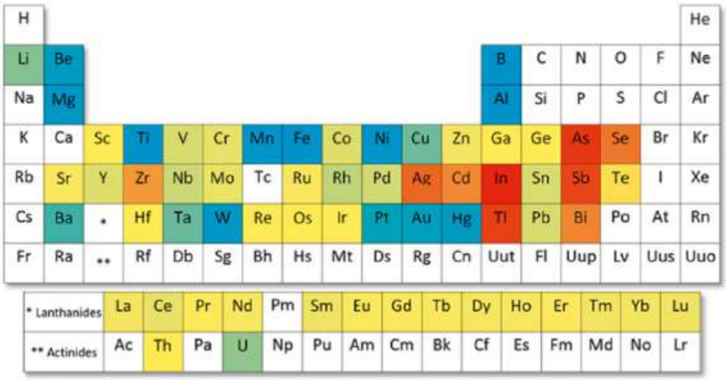
Finally, the vulnerability to supply restriction (VSR), at the global scale, is evaluated by the averaging importance criterium, through its corresponding sub-indicators, i.e. the Percentage of Population Utilizing (PPU), and the Substitutability. In particular, the substitutability is evaluated through three sub-indicators, i.e. the substitute performance (SP), the substitute availability (SA), and the environmental impact ratio (ER), according to

$$VSR_{global} = \sum_i \phi_i \frac{PPU + \frac{SP_i + SA_i + ER_i}{3}}{2} \tag{3.5}$$

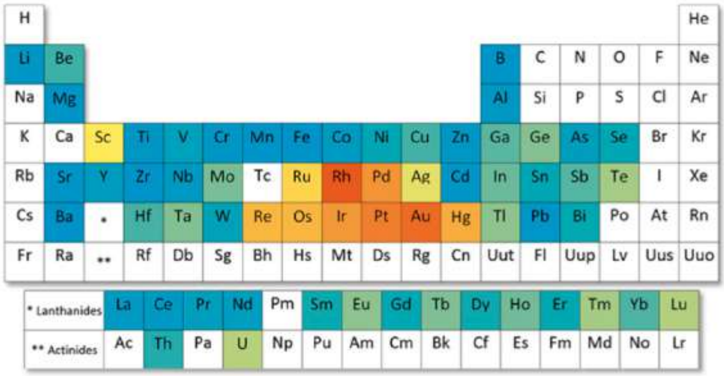
The importance criterium assesses the relevance of a material and the application where the material is used for the global population. The rationale of the PPU sub-indicator is to evaluate the impact of a material on society, by looking at the percentage of total population (a score between 0 and 100) that is using such material. ϕ_i is the end use fraction for end use i, while SP_i represents the performance of the substitute for the end-use i by evaluating the presence of the materials in past products. Finally, the SA indicator is the supply risk (SR) of the substitute material, while the ER indicator evaluates the environmental impact of the substitute ($EI_{substitute}$) to the analyzed material ($EI_{material}$) ratio, according to $ER = 50 \times {}^{EI_{substitute}}/_{EI_{material}}$. With this formulation if the environmental implications are equal, a score of 50 is assigned, while if the substitute impacts twice, or more, than the target material a score of 100 is assigned, the worst score. More details about the methodology and assigned score can be found in Thomas E Graedel, Barr, et al. (2012). ■

Thomas E Graedel, E. Harper, et al. (2015) precisely evaluated the criticality of 62 metals and metalloids and their degree of substitutability. Metals and metalloids in the XXI century are essential for our society, mainly for high tech components and products and for infrastructures required for electricity grid, and power plants. According to a recent article titled “On the materials basis of modern society” (Thomas E Graedel, Ermelina M Harper, et al., 2015), a printed circuit boards of a modern computer, as an example, is composed by 44 different chemical elements. Figure 3.9 shows the three components - SR, EI, and VSR - of the criticality index according to the study of Thomas E Graedel, Ermelina M Harper, et al. (2015) for 62 metals and metalloids. In terms of supply risk (fig. 3.9a), the materials most at risk are the ones necessary for electronic components and products, from laptop to solar cells, as indium, arsenic, thallium, antimony, silver, and selenium. Gold and the platinum group (Ruthenium, Rhodium, Palladium, Platinum, Iridium, Osmium), although largely adopted in high tech products, are not critical in terms of supply but they are the most critical in terms of environmental implications (Thomas E Graedel, E. Harper, et al., 2015) as shown in figure 3.9b. Gold and platinum, in particular, have a high vulnerability to supply restrictions (figure 3.9c) due to their large use in electronics, and jewelry, and geographically limited deposits, respectively.

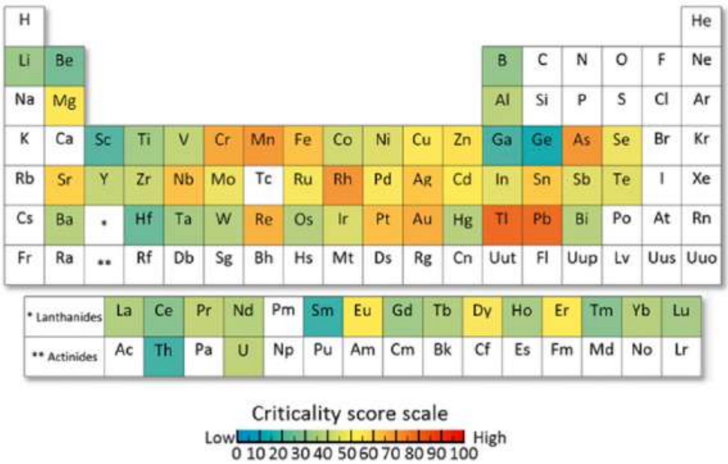
In terms of VSR (fig. 3.9c) several metals and metalloids, from lead, thallium, and arsenic to chromium, magnesium, and several rare earths, exhibit a high risk due to lack of available substitutes. Thomas E Graedel, E. Harper, et al. (2015), finally,



(a) Supply risk



(b) Environmental Implications



(c) Vulnerability to Supply Restrictions

Figure 3.9: The three components of the criticality for 62 metals. Source: (Thomas E Graedel, E. Harper, et al., 2015)

also classified all metals and metalloids into five main clusters, depending on the three dimensions (SR, EI, and VSR), highlighting the main reasons of concern. Table 3.2 summarizes the clusters, and included elements, and their main characteristics. Cluster 1 shows a high VSR but a low SR and includes metals with large deposits on Earth but with difficulty to identify proper substitutes. Metals and metalloids in cluster 2, instead, exhibit high environmental implications due to the extraction process and includes elements as gold and mercury. Cluster 3 mainly consists of rare earth, while the fourth group is composed of specific metals for high-tech products and the fifth of elements with an average score in all the three criticality dimensions. Thus, only a few elements have a high supply risk in the next decades, although in a longer timescale, i.e. a hundred year, the supply risk issue remains. Concluding, lithium, chromium and rare earths, are considered critical in terms of VSR, while gold, platinum group metals and mercury are critical in terms of environmental impacts. The widely debated rare earths do not present a high supply risk (indeed they are largely available on Earth) but they have large environmental implications, mainly due to low concentration of metals in mined rocks. Moreover, they have a high vulnerability to supply restriction, due to the uneven mining sites distribution in the world (Nassar et al., 2015).

Table 3.2: Clusters of metals according to the criticality score. Source: (Thomas E Graedel, E. Harper, et al., 2015)

Cluster	**Features**	**Chemical Elements**
I	SR low VSR high	Li, Ba, Be, B, Ti, Al, W, Mg, Ni, Mn, Fe
II	EI high VSR high	Sc, Ru, Re, Pd, Os, Ir, Rh, Pt, Au, Hg
III	Average values	V, Y, Co, La, Nd, Pr, Ce, Gd, Ga, Hf, Sm, Th, Ge, Cu, Ta, U, Mo, Eu, Te, Tb, Ho, Yb, Tm, Lu
IV	SR high VSR high	Cr, Nb, Sn, Zn, Sr, Dy, Er, Pb
V	Average values	As, Tl, Ag, In, Sb, Se, Cd, Zr, Bi

Similarly to the criticality methodology developed by Thomas E Graedel, Ermelina M Harper, et al. (2015), the European Commission, since 2011, assessed the criticality of dozens of metals and metalloids with respect to the European economy itself (EC, 2020c). In the past years, since 2011, the EC released four technical report on critical raw materials. The last report, released in 2020 (EC, 2020a), analyzed 83 elements, focusing on rare earth, platinum group and other 63 individual elements, identifying 30 critical raw materials (CRMs). The European methodology for critical materials, differently from the one proposed by Thomas E Graedel, Ermelina M Harper, et al., avoids the environmental implication dimension and focuses primarily on two main parameters: 1) the economic importance, and 2) the supply risk. The economic importance indicator evaluates the value added (VA) of the main manufacturing sectors of the European economy where a material is used by adjusting the final score through the substitution index, i.e. the evaluation of possible material substitutes. The supply risk indicator, similarly to Thomas E Graedel, Ermelina M Harper, et al., considers both the global supply, country governance, import dependency, and recycling rate (EC, 2020a, p.20). Increasing recycling rate, or the availability of substitutes are included in the assessment as measure to reduce the supply risk. In the final report, 30 materials[1] have been identified as CRM for the EU economy. In terms of supply risk, the most critical materials are the light and heavy rare earths, followed by germanium, phosphorus, niobium, and magnesium, while, in terms of economic importance, the most crucial materials are the tungsten, natural rubber, magnesium, niobium and cobalt. Natural rubber is not very critical in terms of supply but plays an important role in the EU economy. Many other raw materials, such as chromium, manganese, iron ore, molybdenium, also play a noteworthy role in the EU economy but, currently, are not considered critical in terms of supply risk. With respect to the previous report released in 2017, hydrogen is not considered critical anymore (due to its low economic importance), while bauxite, lithium, titanium and strontium have entered in the critical material list. Relative to the identified critical material for the EU, figure 3.10 shows the global extraction share per material highlighting the top producers. The rare earth global supply, in particular, heavily depends on China. Indeed, more than the 85% global extraction of REE derives from China and more than the 98% of EU supply. Many other raw materials are extracted mainly in China. The 89% of magnesium, the 74% of phosphorus, the 80% of germanium, just to name a few of the most critical raw materials, are produced in China, although some alternative supplier for EU may occur, as the germanium and the phosphorus that are supplied to EU mainly by the Finland and the Kazakhstan, respectively. Cobalt global supply is dominated by the Democratic Republic of the Congo (59%) while niobium is produced almost only in Brazil (92%) and the EU supply mainly depends on them (68% and 85% respectively).

Nowadays, the debate about rare earths is emerging among both academics and policy-makers, especially due to their role in emerging and clean energy technologies. Beyond rare earths and the most critical raw materials, also many other materials such as lithium, cobalt, indium, vanadium and others, with an average criticality score both in terms of supply risk and economic importance could become more and more critical in the next decade due to the essential role they will play in emerging technologies.

Focus 3.3 — Emerging technologies. Recently, the European Commission (EC) published a foresight study (S. Bobba et al., 2020) on critical raw materials for emerging technologies within the European Union (EU). In the report, the authors analyzed the global supply chain of nine future leading technologies - Li-ion batteries, fuel-cells, wind energy, electric traction motors, photovoltaic (PV) technology, robotics, drones, 3D printing, and digital technologies - by highlighting material consumption trends, supply chain bottleneck and risk factors. Figure 3.11 shows the

[1] Antimony, Fluorspar, Magnesium, Silicon Metal, Baryte, Gallium, Natural Graphite, Tantalum, Bauxite, Germanium, Natural Rubber, Titanium, Beryllium, Hafnium, Niobium, Tungsten, Bismuth, HREEs, PGMs, Vanadium, Borates, Indium, Phosphate rock, Strontium, Cobalt, Lithium, Phosphorus, Coking Coal, LREEs, Scandium

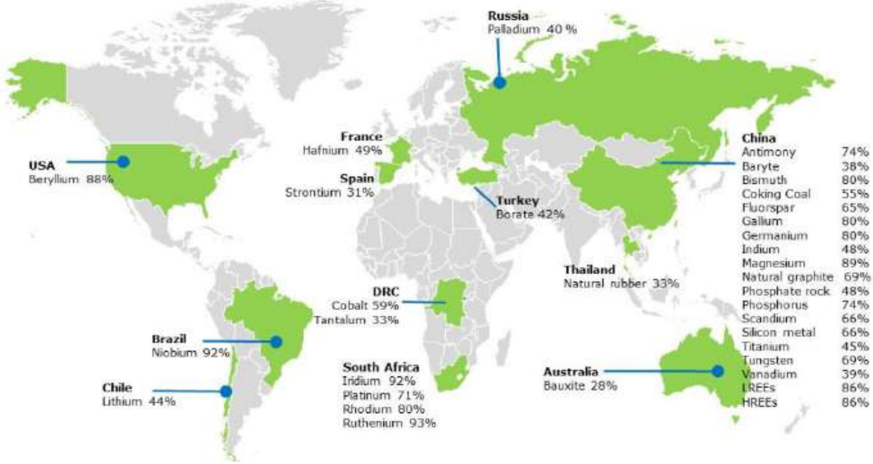


Figure 3.10: Largest share of global supply for the EU critical raw material. Source: (EC, 2020a)

material flows for the 25 analyzed raw materials with respect to nine technologies and three sectors. The colors (red to green) represent the supply risk management for the EU countries. Two predictions on future usages have been included - at 2030 and at 2050 - by considering a multiplying factor, i.e. the no. of times the consumption will double up. Bottlenecks and supply chain risks have been also calculated according to Blagoeva et al. (2019) relatively to four stages - raw materials extraction, processed materials, components, and assemblies. Predictions at 2030 show that, for instance, lithium, cobalt, dysprosium, neodymium consumption will increase by 18, 5, 5, ~ 2 times with respect to the past decade consumption. At 2050, lithium will be over 50 times the consumption of the past decade, while cobalt, dysprosium and neodymium consumption will be 10 times the current consumption. The supply chain risk mainly depends on the material availability and on the market-demand. The materials mostly at risk belong to the so-called rare earths (REEs)[a] group, e.g. dysprosium and neodymium, mainly used for high tech products. Some bottlenecks have been identified at the stage of raw materials (motors, wind turbines, robotics, drones, digital technologies) and processed materials or at components (PV panels, robotics) and assemblies (fuel cells, li-ion cells, drones), depending on local know-how. From the global picture depicted, it is clear that lack of resources or recycling and reusing strategies may affect the whole European Union by (S. Bobba et al., 2020). ■

[a]The 17 rare-earth are cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), scandium (Sc), terbium (Tb), thulium (Tm), ytterbium (Yb), and yttrium (Y)

Concluding, as pointed out by the criticality methodology, the resource exploitation

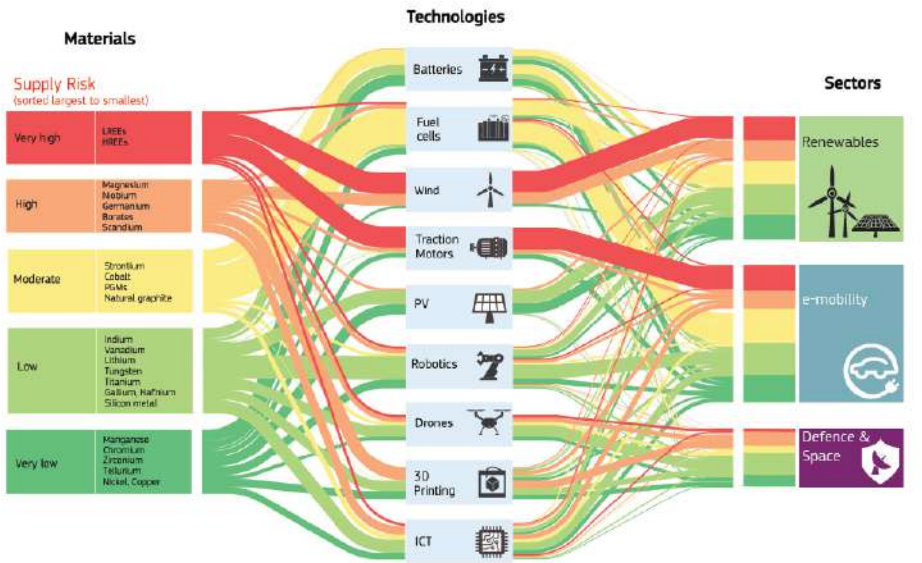


Figure 3.11: Critical raw materials in the European Union. Flows of 25 selected raw materials for nine leading technologies with respect three main sectors. Source: S. Bobba et al. (2020)

should not only considered in terms of depletion of available reserves but also in terms of the induced environemental impacts on environmental. These impacts can be directly related to the exploitation of a particular resource in a territory (e.g. deforestation or an exhausted ore mine) or indirectly, due to the generated externalities (e.g. GHG emissions or acidification), due to the industry processes necessary to extract and treat the raw materials. For instance, the population growth in developing countries can provoke the overexploitation of forest both to produce biomasses or paper (Audu, 2013) or to allow agriculture to expand (Grau et al., 2005). Massive deforestation, thus, may even interfer with local weather by reducing rainfall and increasing the temperatures, generating negative feedback loops for the environment and future agriculture activities that can even cause desertification (Lawrence et al., 2015).

3.2 Materials for societal needs

Resources and raw materials, from minerals and metals to renewable ones, are necessary to satisfy societal needs, from the most basic ones, as housing, health and nutrition, to the unnecessary and optional ones. In a recent report Circle Economy (2019) analyzed and split the global material flows (92.8 Gt) into seven major societal needs: 1) housing and infrastructure (43.8%), 2) nutrition (21.7%), 3) mobility (11.6%), 4) consummables (10.5%), 5) services (5.9%), 6) healthcare (3.9%) and 7) communication (2.7%). Figure 3.12 shows the global share of each societal need in term of the total mass used without

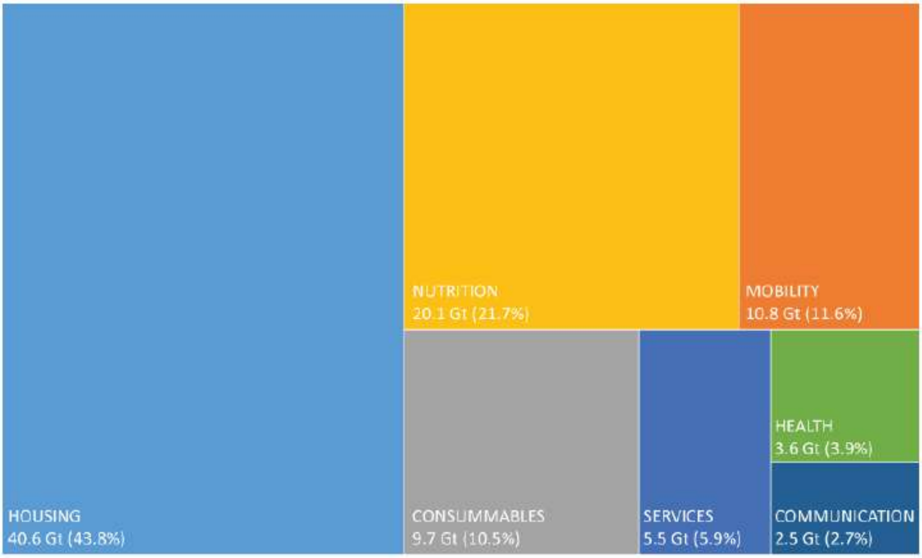


Figure 3.12: Raw materials consumption share (total mass). Seven societal needs are represented. Data source: Circle Economy (2019).

any distinction among biomass, fossil fuels, ores, and minerals. Basically, biomass mainly feeds nutrition, consumables, and services, while fossil fuels are necessary primarily to mobility, healthcare, services, and, in a smaller percentage, to consumables and nutrition. On the contrary, ores and minerals are exploited almost solely by housing, communication, mobility and healthcare (healthcare relies primarily on ores and fossil fuels rather than on minerals).

Housing and infrastructure consists of the construction of new or the maintenance of existing buildings and basic infrastructure as roads, railroads and industry plants. Nutrition counts all materials necessary for agriculture, mobility includes both materials to produce and power all types of transports, from iron ore to produce a car to the fossil fuels necessary to use it. Consummables consist of all products, from clothes to electrical and electronic equipments, from cosmetics to paintures. Services and healthcare include all societal needs from education to hospital, from public services to banking and insurance. Finally, communication includes digital products (e.g. mobile devices) and infrastructures (e.g. data centres) needed in the new millenium to communicate. Such needs, i.e. the communication group, is also an enabler for the circular economy. Table 3.3 summarized the seven societal needs, highlighting a few explanatory examples, and the average lifetime. Indeed, each societal need has a different lifespan and it should be treated differently; food and beverages lifetime is very short (generally less than one year), consumables lifetime varies from a few days (for single-use products, for instance) to a few years (e.g. clothes) or one-two decades (e.g. domestic and household appliances), housing and infrastructure should last decades or, even hundreds years.

Table 3.3: Societal needs and average lifetime. Source: Circle Economy (2019)

Societal Need	**Product types**	**Average lifetime**
Housing	Houses, offices, industries, roads, power plants	medium-long
Mobility	Cars, trains, ships, airplanes, and fossil fuels or batteries	short-medium
Consumables	Clothes, electrical and electronic equipments, dyes and paints, cosmetics, personal cares products	short-medium
Nutrition	Food and agricultural products	short
Services	Education, banking, insurance, commercial activities and public services	short-medium
Health	Hospital disposables, technical equipments, pharmaceuticals	short-medium
Communication	Mobile devices, data centres, networking cables	medium-long

On top of the considerations about the total mass, other meaningful indicators should be considered. For instance, Circle Economy (2019) analyzed the Mass-Value-Carbon (MVC) global values. Mass represents the material flow (expressed in tons of material), as shown in figure 3.12, value the generated income (in €), while carbon the related GHG emissions (in $tCO_{2,eq}$). Figure 3.13 shows the percentage per societal need of the global extracted mass (92.8 Gt), the value generated (58.2 T€), and the GHG emission (50.9 Gt of $CO_{2,eq}$). According to Circle Economy (2019), three groups may be recognized. The first group - housing, mobility, consumables - consume a large amount of material (housing), or generate a large amount of GHG emissions (mobility and consumables) with respect to the value they generate. On the contrary, services, health, and communication generate a high value, although the material need and the generated GHG emissions are low. In-between, the nutrition need generates a very low value, despite the huge impact both in terms of mass and carbon.

From figure 3.13 the global picture is quite clear. The majority of material is used for housing and infrastructure (almost 44%) and for nutrition (22%), while the top contributors in term of CO_2 emissions are the mobility (26%), consumables (21%), and housing (18%) needs. Thus, the *Housing and Infrastructure* are societal need most responsible for the exploitation of materials (third in terms of GHG emission). In the focus 3.4, to better understand the consumption pattern of these top contributors, the material dependence of the built environment sector will be discussed in more detail.

Focus 3.4 — Urban Built environment. Cities and the urban environment always attracted millions of people. From the first industrial revolution onward, the population

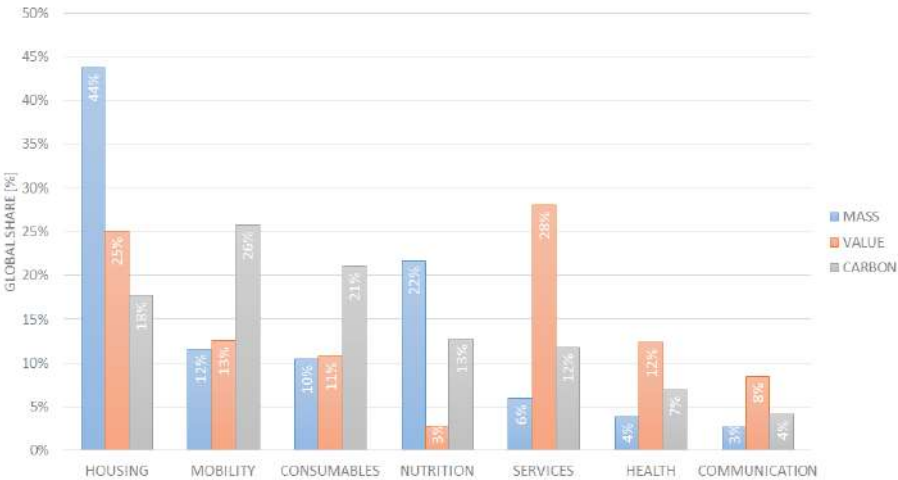


Figure 3.13: Percentage per societal need. Mass, value and carbon emissions are represented. Data source: Circle Economy (2019).

in the urban and metropolitan areas has grown steadily. From 1750 to 1950, during the so-called "first wave" about 400 millions people moved to cities. According to the United Nations Environment Programme, by 2050, the urban built environment will grow by more than 6 billion people and cities will host approximately 70% of the global population (UNEP, 2013). This "second wave" of urbanisation, started in 1950, is occurring mainly in the Asian and African continent. On the contrary, in Europe and North America the built environment is mostly static and the majority of the raw materials used yearly are necessary to maintain, repair, or renovate existing infrastructures and buildings. According to Circle Economy (2019), in Europe, for instance, the building and infrastructure stock accounts for 95 Gt and is slightly increasing by 1% yearly. In 2050, it will grow approximately by 12 Gt (Gallego-Schmid et al., 2020). The relevance of the building sector has been also highlighted by the European Commission. Indeed, currently the housing and infrastructure sector produce about 36% of the total greenhouse gas emissions of the European Union (EC, 2019a). In the past decades, European Directives (EP, 2010; EP, 2012) focused primarily on the so-called operational energy, i.e. the energy used for heating/cooling a building and for lighting and electrical/electronics loads, and on energy efficiency renovations and interventions, completely avoiding the embodied energy and carbon of materials. The embodied emissions, i.e. the emissions related to the production, use, and demolition of a material, for 60-year buildings have been estimated to range from the 31% and 44% of the total emissions (NHBC, 2011), while the embodied energy range from 10% to 30% of the total energy used in the whole life cycle of a building (Ingrao et al., 2019). According to Hertwich et al. (2019), the majority of these embodied emissions derive from the extraction and the production of the materials. Thus, the necessity to focus on the materials' impact, in terms of embodied energy, carbon or other environmental indicators, is undoubted. Globally, the construction sector, from the construction of new buildings/infrastructures to the maintenance and disposal of existing ones, is the largest consumer of raw materials, with 42.4 Gt of raw materials needed annually (Circle Economy, 2019) out of the 92.8 Gt total materials consumption, i.e. around 45% of the global consumption. Its impact on global CO_2 emissions, instead, accounts for about 18% on the total CO_2 emissions worldwide (about 9 Gt of CO_2). Within the construction sector, the majority of GHG emissions (about 2.9 Gt CO_2) derives from the use of cement, lime and plaster (Hertwich et al., 2019). Concluding, in the past decades the high increase of materials demand for the built environment has been mainly lead by the so-called "second-wave" urbanization and by the movement of millions of people from the countryside to cities. Although this trend will continue in next decades due to the economic growth of Asia and Africa, in the long-term it will have a positive effect on the environment by reducing materials demand as discussed by McAfee (2019). According to the economist Edward Glaeser *"If you want to be good to the environment, stay away from it ... Living in the country is not the right way to care for the Earth. The best thing that we can do for the planet is build more skyscrapers"* McAfee (2019, p.92). Indeed, living in high density efficient cities will drastically reduce the energy and materials consumption for both housing and transportation thanks to high efficient construction techniques and smaller distances people have to do daily.

However, as described by Rees (1992) in his treatment on the ecological footprint, a city is not a stand-alone entity, rather it is a sort of resources' sink. Indeed, from the smallest towns up to the biggest metropolitan cities, each one needs a constant inflow of materials, from raw resources for new infrastructure and housing (or for their renovation), for goods, commodities and food for all the population. ■

The second societal need, instead, responsible for the use of material (mass) - fourth in term of GHG emissions - is the *Nutrition* societal need. Agriculture, forestry, fisheries and livestock globally generate around the 20% of total GHG emissions (FAO, 2021). For this reason, the Common Agricultural Policy (CAP) of the EU has been recently supported by the European agricultural fund for rural development (EAFRD) for the period 2021-2027 with around 95.5 billion euros thanks to the rural development programmes (RDPs). With this ad-hoc programme, the European Union aims at reducing the high environmental impact produced in the rural area by financing local actions aimed at fighting climate change, by supporting local actions and promoting smart villages. Similarly and for the same reason, the Food and Agriculture Organization (FAO) of the United Nations focuses on adaptation and mitigation strategies in the agriculture sector developing the Climate-smart agriculture (CSA) framework in order to sustainably increase agricultural incomes, adapting rural area to climate change, and reducing GHG emissions (FAO, 2017).

3.3 Recycling and future scenarios

Taken for granted the huge exploitation of raw materials in the past century, which enormously increased in last decades due to the growth of China and India, and the emergence of several new technological applications, new paths for our society are necessary and urgent. Since the Seventies and the Eighties, industrial ecologists, environmental economists, and other scientists, emphasized the need to introduce and improve the recycling of materials in order to reduce the human pressure on nature and to live within the limits of the planet Earth. Despite a huge effort, for many metals the global recycling rate at the beginning of the last decade was still very low. Figure 3.14 shows the average global end of life recycling rate for sixty metals. Percentages mainly reflect the feature of the products they are used in. Indeed, large recycling rates, such as for iron or copper, correspond to metals used in large appliance or products, as steel in automobiles. On the contrary, chemical elements as indium (used in LCD screens, laptops or solar cells), germanium (used in optic fiber) or lithium (used in batteries) have a very low recycling rate, as a consequence of the complexity of the products and the small quantity in each product (M. Wang et al., 2017).

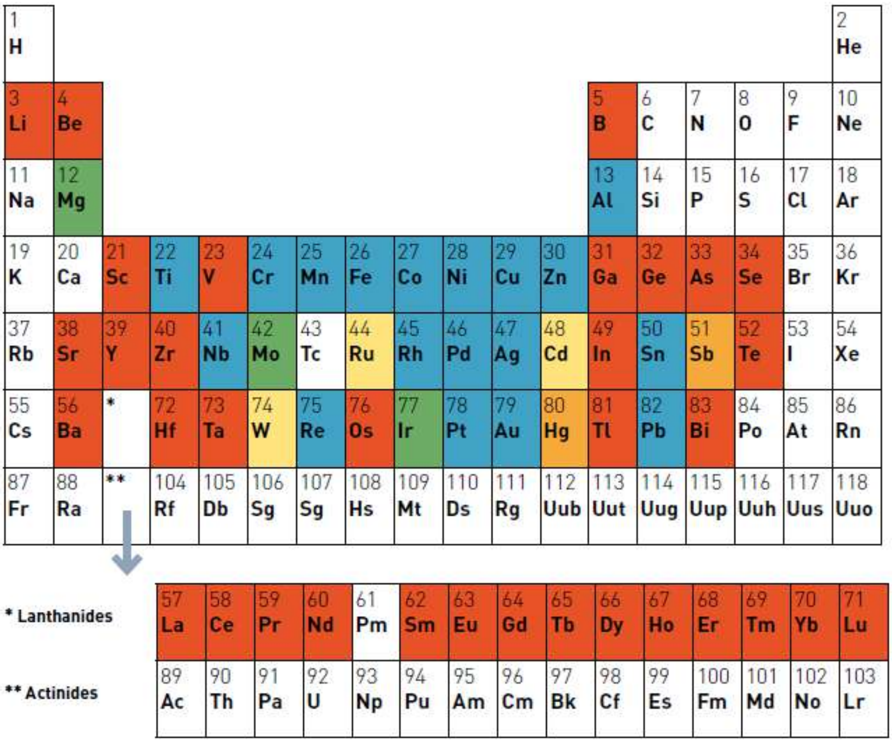
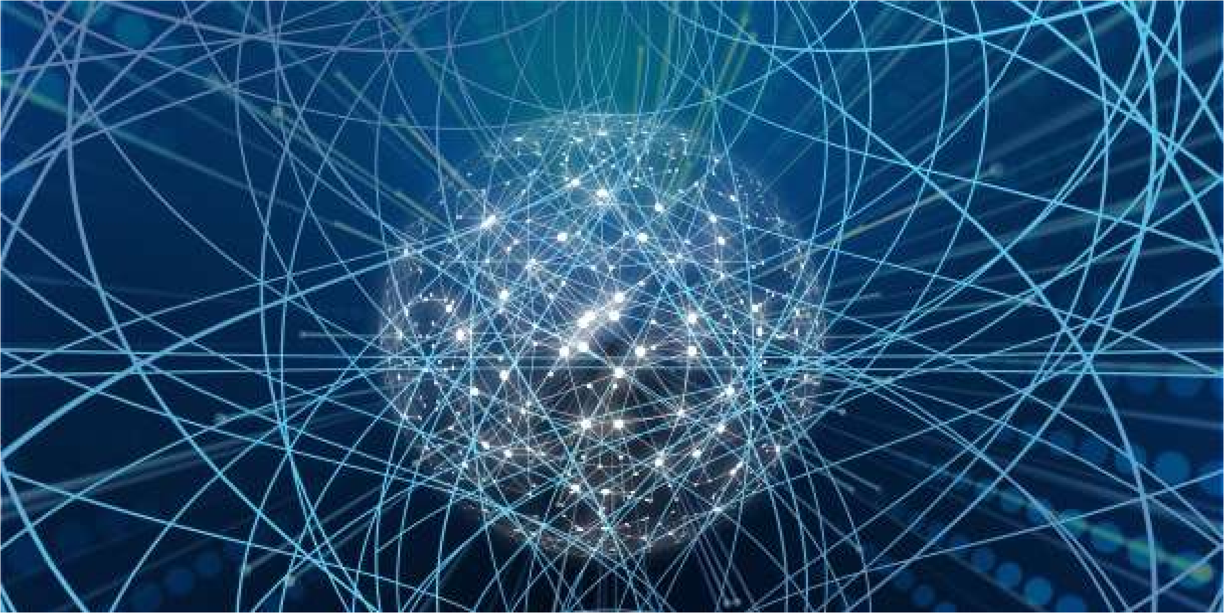


Figure 3.14: Metals' recycling rate. Blue (> 50%), green (25-50%), yellow (10-25%), orange (1-10%) and red (< 1%). Source: (UNEP, 2011)

Beyond recycling rate and material depletion. As previously discussed, starting from the discussion about the resource depletion (Jowitt et al., 2020), the urgency in the short-medium term is not directly related to the shortage of material supply, but it is strictly tied to the criticality of materials, in terms of social, economic and environmental impacts. To go beyond the element recycling rate, a recent article proposed a new composite indicator, named *Chemical Element Sustainability Index* (CESI), to evaluate the recycling rate (RR), the global warming potential (GWP), the human development index (HDI), and the national economic importance (NEI) in order to include the three sustainability pillars (Elkington, 1994). A recent literature review (Cantzler et al., 2020) highlights the mitigation potential of recycling strategies in different sectors.

Skipping the debate on the proper indicator required to monitor and manage the global material flows and on the criticality of materials, it is undoubted that a proper *Information System* (IS) to monitor and engage all relevant stakeholders at a global level is still missing. Although tools, online dashboards, statistical data, as the ones provided by the USGS (USGS, 2020) or UNEP (UNEP, 2020), already exist, it is clear that a proper *"global control room"* open, transparent and accessible, to manage the global common resources, their uses and applications and their end of life, is an open question mark. Moreover, how should a global common pool of resources be managed? Who should be supposed to monitor, control and eventually guide the future of the Earth? To answer to such questions, information are needed, not only raw data, in order to allow to emerge knowledge and wisdom, according to the previously described (see chapter 1) DIKW hierarchy (Bernstein, 2009).



4. Information

Where is the Life
we have lost in living?
Where is the wisdom
we have lost in knowledge?
Where is the knowledge
we have lost in information?
...
What life have you,
if you have not life together?
There is no life
that is not in community

T.S. Eliot (1934)

We live in the *information society* (Webster, 2014). Since the Seventies, humanity is moving from a "purely" industrial society to the so-called information society. In 1972, an information society, in one of its earliest and most visionary definition, has been described by the *Japan Computer Usage Development Institute*, a non-profit organization (NGO), like *"a society with highly intellectual creativity where people may draw future designs on an invisible canvas and pursue and realize individual lives worth living"*. This first definition was focused on the use of the emergent personal computers, but their idea of a future society was much more visionary. Indeed, the NGO delivered to the

Japanese government the *Plan for Information Society - A national goal toward the year 2000*, a national plan to realize *"a society that brings about a general fluorishing state of human intellectual creativity, instead of affluent material consumption"*. Envisioning the future Internet of Things and computer development, in their plan there were (already in the Seventies) the seeds to develop computer controlled vehicle system, automated supermarket, regional health control and cooling/heating system, as well as pollution prevention system and IT educational programmes (Masuda, 1981, p.3-10). In the following decades, many sociologists, philosophers and political scientists analyzed the rapid transformation of the society and the coming of the information society giving different definitions and focusing on precise aspects. Webster (2014, p.10) summarized the analyses in five main groups - technological, economic, occupational, spatial, and cultural - depending on the main point of view highlighted. For further details see the focus 4.1. Regardless of single precise definitions, generally the debate about the information society emerged because of the emergent IT technologies and the rapid transformation of the job market, from industrial and manufacturing activities towards more "abstract" jobs linked to the communication, the world of spectacle, or more in general to highly ethereal and creative jobs. The rapid change of the society involved everything, from the management of the organization to the introduction of the Stakeholder Theory (ST) (Freeman, 1984) and the new millenium intellectual movement based on Open Data (OD) (OKI, 2005), as well as to more "pragmatic" applications like marketing, software development or monitoring plans. More recently, as presaged by the Japanese NGO in the Seventies, researchers and practitioners focused on heating and cooling system by analysing users' behaviour and their relationship with the surrounding environment (e.g. a building) (Cottafava et al., 2019). This last frontier of research explores how, through information and the use of new technologies, users' behavioural change may occur, or even may be induced, penetrating even the people behaviour and opening new scenarios and research fields from the education for sustainable development, and experiential learning to human-machine interactions.

Focus 4.1 — Information Society. According to Webster (2014, p.10-23) there are five typical definitions of an information society involving different fields and aspects: 1) technological, 2) economic, 3) occupational, 4) spatial, and 5) cultural.

The first to appear has been the technological one in the Seventies with the introduction of the personal computers and the mass adoption of Information Technologies (IT). The technological aspect may be divided into three main phases: 1) 1970-1990, with the diffusion of the personal computer, 2) 1990-2005, with the introduction of the World Wide Web and the computer communications, and 3) 2005-onwards, the social media period. The economic definition lies mainly on the importance of the monitoring and control of every economic activities, in terms of GDP at national and international level, or simply in terms of budget accounting at corporation and organization level. Moreover, the prevalence of economic activities strictly tied to information jobs brought academics to focus on the economic aspect of the information society. Similarly, the occupational definition emerged with the work of Bell (1976) about the "The coming of the post-industrial society". With respect to the occupational aspect, the information society, originally defined by Bell as post-industrial society, has began because of the declining of manufacturing jobs and the majority of the job positions was/is related to information works and to the service sector, from education to communication, up to management and software development. In the spatial definition, the concept of a *wired society* or a *network society* is crucial. In this case, the focus is on the *radical revision of time-space relations*, from personal and private relations up to global logistics (Webster, 2014, p.20). From the cultural point of view, instead, the definition of information society arises because we inhabit in a *media-saturated environment* (p.22). We are living in the *Society of the Spectacle*, full of signs and symbols, where, as stated by Debord (2012, p.11), *the spectacle is capital accumulated to the point that it becomes images*.

In Webster's opinion, none of the previous definitions may define the current information society as it is. Each definition lacks specificity and, in some cases, it may be generalized to previous epochs, or, in other cases, it cannot describe thoroughly the current societal foundation. For instance, in the case of spatial or technological information society, one can argue that also with the discoveries of the radio, telephone, or telegraph the space relations had been radically transformed. In the case of the cultural definition, the loss of meaning of *signs*, due to the redundance and overabundance of communications, undermines the very definition of an information society where the reality itself is questioned. This overabundance of signs and symbols brought to the *death of signs*: the signs themselves have lost their meaning, become self-referential, a *hyper-reality* as defined by Baudrillard. Using his words, *"we live in a world where there is more and more information, and less and less meaning"* (Baudrillard, 1994, p.79). ■

According to Baudrillard (1994), the overabundance of information in our society is eroding the meaning of information, undermining the reality itself. In my opinion, the very beginning of the information society has not yet come. Its definition is still rough and highly debated (see focus 4.1), since the definitive *fil rouge* and aim has not been properly identified and divergent points of view still exist. The ultimate scope of a society, intended as a complex ecosystem (Gobble, 2014), is to thrive, and, as in the past, each transition, from primitive society to subsistence economy, from pre-industrial to the industrial economy, was dominated by a deep change in the relationships and its role with respect to the surrounding environment. For this reason, I think, the challenge we are currently facing about the planetary boundaries, climate change, and many other urgent environmental issues cannot be solved only with a positivist approach. The first distinguishing feature of positivist philosophy and sociology (founded in the XIX century) is that, using the words of its founder Comte (1858, p.28), *"it regards all phenomena as subjected to invariable natural Laws. Our business is - seeing how vain is any research into what are called Causes, whether first or final - to pursue an accurate discovery of these Laws, with a view to reducing them to the smallest possible number"*. On the contrary, the anti-positivism and post-positivist schools of thought claim that the observer cannot be truly independent from the thing who is observing. Roughly speaking, this is the position of the humankind within nature itself, as part of it (Wahl, 2016). The main difference is in the time-scale of the observer influence. Instead of an immediate or short-term consequence, humanity, by attempting to “observe” and regulate Nature, is provoking medium-long term impacts that cannot be perfectly neither observed nor predicted. Moreover, the current urgency due to the climate change, the difficulty to take immediate actions based on partial information, due to the complexity of natural ecosystems, and the impossibility to precisely predict the behaviour and response of an ecosystem to particular stimuli, affect any possible positivist approach and makes impossible to wait. Indeed, in my opinion, to face the climate and environmental crisis a *natural post-positivist* approach, similarly to social anti-positivism and post-positivism schools of thought, is the path to react to the current challenge. Thus, looking for social and behavioural change based on the partial available information on the World may be the right direction. The co-evolution of positivist and post-positivist approaches, may be depicted according to Figure 4.1. Although positivist and post-positivist approaches are generally seen partially in contrast, in my opinion, positivist sociology focus may be seen as a sub-domain of post-positivist theory. In post-positivist sociology, indeed, qualitative analyses substitute quantitative ones (Robson, 2002), and, thus, a larger target of phenomena may be addressed as the interactions among humans and the surrounding environment in particular settings. For this purpose, in the late Seventies the environmental sociology, youngest son of human ecology, emerged as a research field focused on the interactions between the environment and the society (Catton Jr et al., 1978; Dunlap et al., 1979). For further details on environmental sociology see the focus 4.2. On the other hand, positivist natural science is partially in contrast with the rough boundaries and methodologies of post-positivist sociology. A post-positivist natural science, instead, with the use of modelings and simulations, may embrace both theories, avoiding the dualism humans-environment of environmental sociology, focusing directly on the environment and ecosystems to deal with the current climate crisis with a rapid response towards a mass behavioral change.

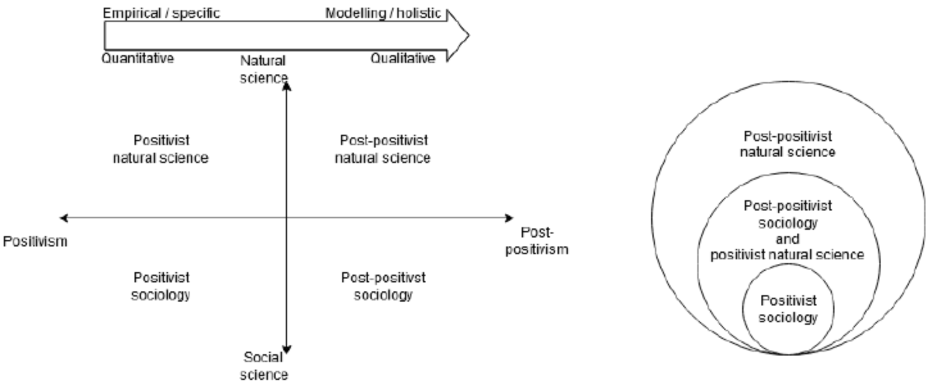


Figure 4.1: Positivist and non-positivist theories.

In this sense, systems dynamics and, more in general, systems thinking provide the proper methodological tools to analyze complex systems (e.g. natural or socio-technical systems) and their dynamics (D. H. Meadows, 2008). Systems thinking and dynamics, born in the Fifties as a branch of cybernetics, analyze complex system by looking at the causal interrelationships among the components of a system rather than looking at the single parts as stand-alone entities. Similarly, the concept of *Warm Data* (i.e. relational information), introduced by N. Bateson (2017b) following the work of her father G. Bateson (1972), should be the proper approach to cope with the ecological issues. Warm Data represents the information and knowledge of a complex system provided and generated by the relational interdepence among its componentsprovides the information about systems' relational interdependence. Warm Data can be defined as (N. Bateson, 2017a):

Definition 4.0.1 — Warm Data. Transcontextual information about the interrelationships that integrate a complex system.

A contextual approach, hence, should aim at *looking for pattern* with an holistic approach rather than looking at the single components (reductionist approach). The two approaches are not in contrast but complementary and findings are equally important; with her words *"Information derived by zooming in on detail is as important as the information derived by zooming out to study context"* (N. Bateson, 2017a). Warm Data idea arose starting from the concept of *Ecology of mind*, introduced by Gregory Bateson. Bateson proposed to focus on *how we think* rather on our actions in order to understand the evolution of social systems and the emergence of new ideas in individuals. As defined by Bateson, similarly to biological ecology which studies the evolution of ecosystems, the Ecology of Mind is an interdisciplinary approach to understand patterns and changes in consciousness. Consciousness, and mind, hence, may be considered like a biological ecosystem where ideas act as the actors (e.g. animals, plants) of the system, and may evolve, born, and die (G. Bateson, 1972).

This brief digression does not undermine or put in discussion the scientific method or the positivist philosophy, rather it attempts to merge them with a dynamic point of view. As discussed by T. Kuhn (2012) the scientific theories are not absolute, but they should be considered as the best state-of-art model to describe the reality till too many unanswered questions emerge. At that point, a new theory comes out to expand or substitute the previous one. In other words, in the current paradigm transition, social and natural science cannot be seen anymore as distinct fields, but they need to merge, as recent studies on socio-ecological systems correctly pointed out (Raum, 2018). For this purpose, in the Seventies the environmental sociology emerged as a research field focused on the interactions between the built and the natural, between the environment and the society (Catton Jr et al., 1978; Dunlap et al., 1979) in order to explain the emergence of the first wave of environmental movements and their critiques. In the same way, a natural post-positivist approach should lead to an ecosystemic answer to the current global environmental challenges by overcoming the dualism society-environment, freeing the natural sciences from purely positivist approaches, and integrating the dynamic essence of the relations among things, real or abstract, as discussed by Cetina (2001) in its article on post social relations. Indeed, in the information society, neither an object of knowledge nor the relations between human and things are static. According to her opinion, *"objects of knowledge in many fields have material instantiations, but they must simultaneously* *be conceived as unfolding structures of absences - as things that continually "explode" and "mutate" into something else"*. The built-natural environment dualism will be specifically addressed and discussed more in depth in next chapter about new paradigms, while in this chapter, instead, starting from the open data movement (section 4.1) I will discuss the reason of the information within the introduced energy-material-information nexus in order to define a *Circular Commons*, following the discussion of Ostrom (1990) and Rifkin (2015).

Focus 4.2 — Environmental sociology and human ecology. Environmental sociology has born in the Seventies, as a response to the emergent environmental social movement and the necessity to interpret its roots. Indeed, at that time, sociology was not facing correctly the emergent environmental issue and was still tied on a totally anthropocentric point of view. According to Catton Jr et al. (1978), indeed, the old sociological paradigm, named the *human exceptionalism paradigm* (HEP), was based on four points: *"1) humans are unique among the earth's creatures, for they have culture, 2) culture can vary almost infinitely and can change much more rapidly than biological traits, 3) thus, many human differences are socially induced rather than inborn, they can be socially altered, and in convenient differences can be eliminated, and 4) thus, also, cultural accumulation means that progress can continue without limit, making all social problems ultimately soluble"*. On the contrary, the *new environmental paradigm* (NEP), as originally stated in the paper "Environmental sociology: A new paradigm" in 1978, was based on three more principles, defining the role and space of humans within the environment: *"1) human beings are but one species among the many that are interdependently involved in the biotic communities that shape our social life, 2) intricate linkages of cause and effect and feedback in the web of nature produce many unintended consequences from purposive human action, and 3) the world is finite, so there are potent physical and biological limits constraining economic growth, social progress, and other societal phenomena"*. According to Buttel et al. (2002) environmental sociology is characterized by a *double determination*, i.e. about how to consider humans and nature relationships (if *in the web of life* and *as creators of unique and distinctly social environments*). Indeed, on one side, environmental sociology is based on social theory, and, on the other side, to the society-nature relationships. Thus, in other words, environmental sociology focuses on the interactions between the *built environment*, i.e., in its broadest meaning, everything artificial built and created from humans, and the *natural environment*. With respect to the built environment, the focus is about how the built environment may affect people or may induce some particular behaviours. On the other hand, how does the natural environment affect the society and the built environment? Such questions did not emerge only in the Seventies with the environmental sociology, but they were quite common also in the XIX century and at the beginning of the XX century within the so-called human ecology. Human ecology, indeed, aimed and aims to understand the *"structure and change in sustenance organizations or resource groups which support human populations within dynamic and constraining environments"* (Buttel et al., 2002). Pioneering studies in the first half of the XX

> century, for instance, focused on human population in cities and relative evolutionary dynamics. R. E. Park (1936), inspired by Darwin studies, saw cities as a *"web of life"*, and identified *competition* and *cooperation* as the two fundamental *"human interactions through which organized populations struggle to maintain an equilibrium within a constantly changing environment"* (Buttel et al., 2002). More recently, in the Nineties, the global environmental change (GEC), defined by some academics as a *social construction* (Wynne, 1994) - from climate change to ozone destruction or biodiversity loss - gave to environmental sociology and human ecology studies a new wave.
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4.1 Open data

Information is power.
But like all power,
there are those who want
to keep it for themselves

Swartz (2008)
Guerilla Open Access Manifesto

The text of this section is partly based on and adapted from *Easy Open Data* (Dario Cottafava, 2018).

Open means anyone can freely access, use, modify, and share for any purpose. This very general definition, given in 2005, derives from the *Open Knowledge International* and it is the first attempt to define the open concept, in the most general way. The open definition sets the precise meaning of the word open related to any general human knowledge in order to stimulate participation and interoperability. Similarly, open data has been defined as (OKI, 2005):

> **Definition 4.1.1** Open data and content can be freely used, modified, and shared by anyone for any purpose

The open definition traces back to the open source definition, which was derived from the *Debian free software guidelines* and the *Debian social contract*, created by Bruce Perens and the Debian Developers. The open definition arose from a long history related to free software, begun in the Eighties with the definition of copyleft and the four essential freedoms of a software: i) the freedom to run the program as you wish, for any purpose (freedom 0), ii) the freedom to study how the program works, and change it so it does your computing as you wish (freedom 1) iii), the freedom to redistribute copies so you can help your neighbor (freedom 2), and iv) the freedom to distribute copies of your modified versions to others (freedom 3). Access to the source code is a precondition for this, as for open source software (GNU, 2019).

1980-2000: the free software movement.

Free software
is a matter of liberty, not price.
To understand the concept,
you should think of
free as in free speech,
not as in free beer

GNU (2019)

Copyright license (Fig. 4.2 on the leftside) is adopted by authors who want to prevent contents to be reproduced, shared and distributed, modified or mixed by other authors. On the contrary, copyleft (Fig. 4.2 on the rightside) is a license which allows other authors to reproduce, distribute, adapt and modify contents under copyleft license, forcing to maintain the same licensing agreement. Copyleft was ideated by Richard Stallman, in 1984, in order to block and reduce the so-called software hoarding. Richard Stallman, to prevent private companies (or people) to steal software under the public domain, introduced the first copyleft license, the GNU GPL (General Public License) in 1989. Copyleft license allowed to give an ownership to some contents in order to protect them to be exploited for commercial use by other authors. Derived works should be reproduced and distributed under the compatible copyleft scheme depending on the original contents, and a software with the GPL should continue to be *free*, as intended by the Free Software Foundation with the four freedoms (GNU, 2019). During the subsequent ten years, various other similar licenses have been released. The GNU LGPL (Lesser General Public License) was written in 1991 again by Richard Stallman, together with Eben Moglen, to adapt the strict copyleft of the GPL to other more permissive licenses, as the MIT or the BSD (Berkeley Software Distribution) licenses. It allows to use software LGPL even into proprietary software without the requirement to release the source code of derivative works. The BSD license is more permissive and a BSD licensed software can be modified for any purpose and the derivative work can be non-copyleft, thus, without releasing the source code. The MIT license, like the BSD license, is a permissive free software license which allows to reuse software and code within proprietary software with the only clause of including the MIT license in any derivative work. The first wave of citizens, claiming a higher right to make profit, was composed mainly by coders and developers and the legal dispute was basically focused on software. With the new millenium, the legal debate about right and duties on intellectual properties moved on a different level, including any creative content.

Figure 4.2: Copyright VS copyleft.

In January 15, 2001, Lawrence Lessig, Hal Abelson and Eric Eldred founded the

Creative Commons (CC) (CC, 2021a), an American non-profit organization with the aim to expand and legally support creative works. The organization created various licenses, the Creative Commons licenses, filling the gap from copyright-licenses and totally free content licenses with a range of intermediate licenses, completely free of charge for the authors. CC organization introduced easy-to-use one-page licenses, with corresponding symbols in order to quickly recognized author's rights. A CC license is adopted if an author allows contents to be reused, shared or remixed. The licenses are based on the mixing of 4 basic permissions, each one represented by a different symbol (Figure 4.3), and there exist several combinations. From 2001, five upgrades have been released. The last update, version 4.0, has been released in July 2017. The four symbols respectively represent:

- attribution (BY): authors may copy, distribute, display, remix, perform the work and make derivative works, only giving to the author the attribution (credits);
- share-alike (SA): authors may distribute derivative works with the same license of the original work, as for copyleft. Without SA, derivative works might have more restrictive licenses;
- non-commercial (NC): authors may copy, distribute, display, remix, perform the work and make derivative works only for non-commercial purposes;
- no derivative (ND): authors may copy, distribute, display and perform only verbatim copies and not derivative works.

Figure 4.3: Creative commons symbols. From left to right: creative commons (CC), attribution (BY), share-alike (SA), non-commercial (NC), no derivative work (ND).

The four symbols can be mixed and combined depending on author's wishes. The last two permissions, CC-NC and CC-ND, are not free content licenses. In total, there are 7 typical legal combinations. The license spectrum, from public domain to all right reserved is: the CC0 public domain, CC-BY, CC-BY-SA, CC-BY-NC, CC-BY-ND, CC-NC-SA, CC-BY-NC-ND (CC, 2021b). The former three (CC0, CC-BY, CC-BY-SA) satisfy the open definition, as recognized in 2014 by the Open Knowledge Foundation (OKI, 2005), and they allow to share, remix and use the content for commercial purposes, while the last two (CC-BY-ND, and CC-BY-NC-ND) licenses are the most strict and they only permit to share the content.

2000-2020: the open data movement. In the new millenium the free software movement generalized their principles to open data and public content launching the Open Government (OG) movement. In 2007 in California, at the Open Government Working Group - group composed by researchers, professors, entrepreneurs and activists as Tim O'Reilly, the founder of O'Reilly Media, Lawrence Lessig, Professor at Harvard University and Aaron Swartz (Public Resource, 2018)- the first guideline about the Open Government Data (OGD) was written. The defined guideline for Open Government Data was composed by 8 basic principles. Generally, OGD must be *complete, primary, timely, accessible, machine readable, non-discriminatory, non-proprietary* and *license-free*. In a few years, the Open Government was recognized at the highest level. In fact, the OG could be considered a movement initiated in 2009, thanks to the U.S.A. President Barack Obama, who signed "The Memorandum on Transparency and Open Government" within the Transparency Directive of the White House. Within the Memorandum, essentially, the U.S. government assumed to be *transparent, participatory and collaborative* (Obama, 2009). The main goal of the OG is to enable, promote and empower transparency and citizens public participation through the cooperation among different levels and stakeholders of our society, from public administrations to private company, from politicians to scientists and private citizens. One year later, in 2010, the Sunlight Foundation, starting from the first guideline defined in 2007, added two other basic principles related to the *permanence* and *usage costs* (Sunlight Foundation, 2010). During 2011, the Open Government Partnership (OGP) was founded by 8 countries (U.S.A., Brazil, Mexico, U.K., Norway, Philippines, Indonesia and South Africa), with other 38 countries declaring the interest to join the partnership, to assume national commitments and to spread it worldwide. Basically, the OGP aims to promote transparency, fight corruption and empower citizens (OGP, 2011b). In order to join the OGP, a national government should endorse the open government declaration through its letter of intent. The basic values and principles of the open government declaration (OGP, 2011a) span from increasing the availability of information about governmental activities to support civic participation, to increasing the accessibility to new technologies for accountability. Governments who signed the declaration accepted to *"provide high-value information, including raw data, in a timely manner, in formats that the public can easily locate, understand and use, and in formats that facilitate reuse"*, *"enable greater collaboration between governments and civil society organizations and businesses"*, and *"commit to having robust anti-corruption policies, mechanisms and practices, ensuring transparency"*, just to name a few principles. Currently, more than 75 countries has endorsed the open government declaration. Open (government) data has become the crucial aspect to ensure transparency and citizens public participation, as well as the main approach to release information and dataset in different formats. In the European Union, in the past year, the EU Commission also started the path towards the open government data. In particular, Neelie Krose, Vice-President of the European Commission and responsible for the Digital Agenda, issued a data portal for the European Commission in 2012. Within the digital agenda 2011-2015 (EC, 2010a) and the European e-government Action Plan 2011-2015 (EC, 2010b), open data gained a central role within the EU policy. As a first result, since 2015, the European Data Portal (EU, 2021b) has been created and funded by the European Commission and supported by an EU Open Data Portal (EU, 2021a) where datasets from EU countries and public institutions can be found as well as information and toolkit to re-use the data.

Any open (government) data project, or platform, needs some fundamental features.

In particular, one of the most important aspect is to allow the interoperability among different datasets. The interoperability should be guaranteed thanks to a common standardization for any open dataset and an interlinkage through online resources. For this reason, in the last years, the linked open data (LOD), has been introduced. The path to LOD, has been initiated in 2010, when the 5-star model was introduced (Berners-Lee, 2012). The 5-star classification has been invented by Tim Berners-Lee, the inventor of the World Wide Web in 1990 together with Robert Cailliau, and it consists in a general classification for Open Data based on costs and benefits. More precisely, each open dataset can be released in different formats. Depending on the formats and the openness, the open dataset has a general rank in the 5-star model. A simple .pdf is the lowest and worst OD format. Files such as .xls or .csv an intermediate rank (two and three stars), while RDF and LOD the best way to release data on the web. Simply, RDF provides an URL to identify the dataset and facilitate coders and citizens to access it, while LOD connects and links a single dataset to all other available LOD to provide a context to the dataset. Depending on the file format, and consequentely on the rank in the 5 star model, each open dataset improves benefits or costs for both publishers (the original owner of the dataset) and consumers (stakeholders who will use the dataset). Generally, 1 and 2-star opendata (PDF and XLS) are simple to publish for the publisher, but they don't allow consumers to directly process information within the dataset in real-time. Instead, 3-star opendata (CSV) are still easy to publish for the publisher and, moreover, they allow consumers to directly access online to the dataset. 4-star (RDF) and 5-star (LOD) datasets, on the contrary, need a harder and time-consuming work for the publishers (publishers need a more complex platform which needs maintenance and IT specialists), but they allow consumers to constantly access to datasets in real-time, to link OD from any other place on the web. Finally, 5-star OD allow consumers to also know completely the data schema and, consequently, to better exploit data information correlating it with any other available data on the LOD network.

4.2 Circular Commons

In the previous sections, what is an information society and the history and the evolution of the Open Data movement have been introduced, by briefly focusing on the main principles, licenses and tools related to Open Data. On top of these considerations, how could these tools support the global transition towards a sustainable Planet? Where to point to? Under which natural and physical constraints has a global living lab to be imagined and defined? And towards which condition and system state? To give an answer it is necessary a historical view to get tips and insights from thinkers of XIX and XX century who deeply debated about Human Ecology and the management of finite resources, or as defined by Ostrom (1990) *common-pool resources*.

4.2.1 Population dynamics.

The debate about the limit of the planet Earth and about the scarcity of resources traces back to the XIX century in economics. Malthus (1798) in his book *An Essay on the Principle of Population*, originally published anonymously in 1798, studied and described population growth trends, in England and in other countries, and the relationship with scarce resources. Using Malthus's words, he stated *"That the increase of population is necessarily limited by the means of subsistence, That population does invariably increase when the means of subsistence increase, and, That the superior power of population is repressed, and the actual population kept equal to the means of subsistence, by misery and vice"* (Malthus, 1798, p.44). Thus, the population increases until enough resources are available, and stops to grow when there are not enough resources, mainly food, causing, first, inequality and, eventually, famine or wars. According to his analysis, the achievement of such a catastrophe, i.e. the *Malthusian catastrophe*, was inevitable because of different trends in population, which increases exponentially, and in food and resource production, which increases linearly, causing a lack of resources and consequently a reduction in the population. Although in the XX century, population trend, especially in Western society, has been demonstrated to be radically different from the infinite exponential growth as depicted by Malthus, the global population has not yet reached its limit and is still growing, mainly due to developing countries economic growth (Van Bavel, 2013). The stabilization in the population growth is caused by several social and natural factors, as the high level of education, which induces a reduction in the average number of children, the carrying capacity of a territory, or by many other cultural and social factors as late marriage, as in Ireland, induced abortion, as in Japan, or by contraception (NAS, 1963). Indeed, generally, the population growth follows a logistic curve, rather than an exponential one, reaching a dynamic equilibrium when the population pyramid of a country change from a pyramidal shape to an onion shape (Richmond, 2002), as shown in Figure 4.4, moving from an expansive trend to a stationary one. The population pyramids can be explained in terms of positive and negative momentum (Van Bavel, 2013). Western countries, in Europe for instance, have a negative momentum - pyramid on the right in fig. 4.4 - and population already reached its peak; on the contrary, developing countries have a positive momentum - pyramid on the left in fig. 4.4 - and population is still growing. Even in the case of suddenly adopting a population control policy in developing countries, as suggested by D. H. Meadows, D. Meadows, et al. (1972) and other thinkers of the past century, the population will continue to grow for the next decades due to the past years trend. This effect, known as *demographic inertia*, is inevitable to move from the expansive population (shown in fig. 4.4 on the left) to the stationary and constrictive population. Focus 4.3 shows more in detail the misunderstanding of Malthus regarding population growth.

The debate about population growth and human ecology evolved and changed alongside the last century following different schools of thought and analysing different social and technical factors which may affect the population growth. In particular, in the initial treatment of Malthus (1798) technological improvements were already discussed but the real improvement due to the first and second industrial revolutions, and all the XX century discoveries, were impossible to predict. Indeed, in the first half of the XX century, the overcoming of the Malthusian catastrophe was inspired by Durkheim (1933) with his essay on *The Division of Labor in Society* due to social factors, the division of labor, and to technological improvements. In the Fifties, following the discussion on the influence of different social and natural factors, the POET (population, organization,

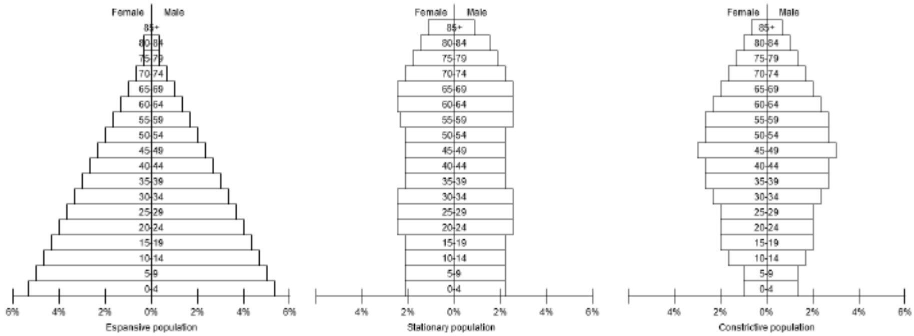


Figure 4.4: Population pyramids. The three shapes refer to three population growth trends: expansive, stationary and constrictive. Adapted from Richmond (2002)

environment, and technology) model was proposed by Duncan (1961), in his article "From social system to ecosystem", to investigate the interconnection about the four distinct features in human ecology. As described in the original article, for instance an increase in pollution may affect both population and organization in a negative way ($E \rightarrow P, E \rightarrow O$). This effect, can activate a balancing feedback loop, a response to develop a technological solution to solve the environmental issue ($O \rightarrow T \rightarrow E$) and so on. In the Sixties, the population issue emerged again, thanks to a few groundbreaking books and reports. *The Population Bomb* (Paul R. Ehrlich, 1968b) book and the already discussed *The Limits to growth* (D. H. Meadows, D. Meadows, et al., 1972) stimulated again the academic debate, as well as the policy and decision-makers vision. According to Van Bavel (2013), the debate about population dynamics should focus on the negative consequences such as poverty and famine, and mass migration dynamic, and not as originally stated and discussed by Malthus on the different rate of food production and population growth. Indeed, poverty and famine are not a consequence of the lack of land and space but of political causes as social and economic inequality, wars and other factors (Van Bavel, 2013). Although the role of "external" factors have been widely studied, human ecology is still deeply founded on Malthusian theory as any assessment on the future of the Earth is based on population growth and related needs, and even if environmental sociology and human ecology have more than fifty years of history, there is still debate on how different levels (e.g. technological innovation or carrying capacity), within a complex ecosystem, interact affecting each others (Buttel et al., 2002).

Focus 4.3 — Looking at the big picture. The population growth generally has been intended as an exponential curve (without constraint and when birth rate is greater than the death rate), while introducing the carrying capacity of the supporting ecosystem it has been modeled as a logistic curve. The population P, considering a carrying capacity of K (in terms of maximum population), in a simplified model

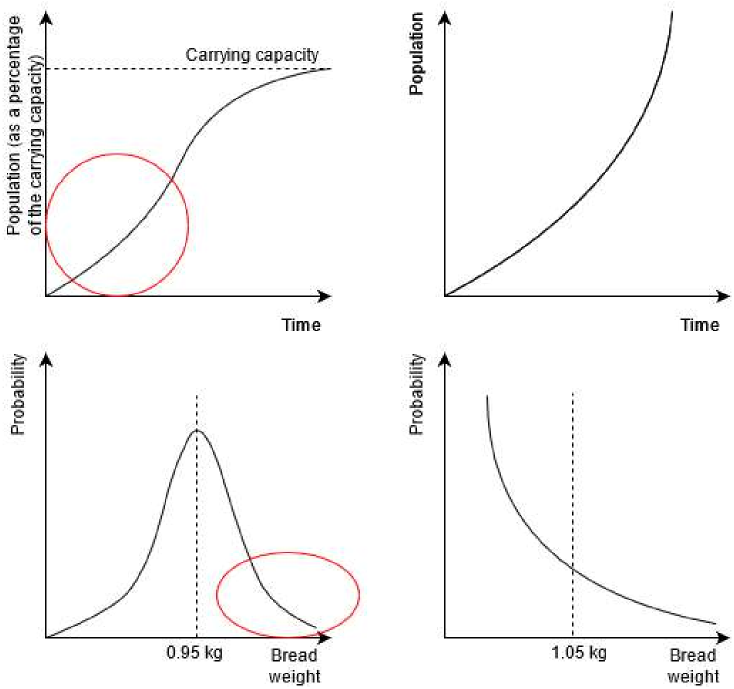


Figure 4.5: Two examples of wrong conclusions.

follows a logistic curve, as follow:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) \tag{4.1}$$

where r is the growth rate coefficient (birth rate minus death rate) and t is the time. The error of Malthus in his model was twofold. First, by looking at historical data, he assumed that food production (i.e. a carrying capacity) would continue to grow linearly and the population exponentially. Obviously, at the time it was not possible to predict the impact of technology improvement (e.g. fertilisers) or the social stabilizing factors (e.g. higher education) for the population growth. Second, as a consequence of wrong hypothesis, he looked at a partial trend as shown in the top two graphs in Fig. 4.5. The top two graphs in Fig. 4.5, indeed, show the exponential trend (population growth without constraints) and the logistic curve (with carrying capacity). The red highlight points out the part of the curve Malthus was looking at. The bottom two graphs, instead, refer to a curious myth regarding Henri Poincaré. The story regards the bakery in Paris where he daily bought 1 kg of bread. Thinking to be defrauded he started to weight every day the bread he bought. Originally he discovered that the average weight of the bread was 0.95 kg and not 1 kg as it was supposed to be. Thus, he reported the fraud to the police. Consequently, from that day the baker started to give him only the biggest bread without really changing the bread production. Poincaré, unsure about the honesty of the baker, measured again the average weight, and he found a probability distribution like the bottom right one, i.e. the right tail of the Gaussian distribution, discovering again the fraud.

This brief story is only to point out how wrong hypothesis or a shortsighted model affect the accuracy of predictions and conclusions. In this and in the previous chapters, we saw how, blinded by the environmental crisis, these misunderstandings commonly occurs. Only by looking, or at least attempting to look, at the *big picture* a model can correctly support the humanity in the ecological transition. ▪

4.2.2 An environmental governance.

Assuming that the global population will not grow forever exponentially, but it will follow a global logistic curve similar to the dynamic followed by the developed countries, reaching likely its peak in this century around 10-12 billions people (Van Bavel, 2013), the main concern at global level, as partially anticipated in the previous chapter, is mainly related to social, economic and environmental issues. Recalling the treatment of Rovers (2019) about the physiological needs, the main challenge to be faced is how to provide 10 billions people with the fundamental needs (e.g. housing, food, energy) and all the "supplementary" needs remaining in the planetary boundaries, as brilliantly described by Raworth (2017). Moreover, the limit of resources should not be intended as urgent as recently emerged in the public opinion, and as popular newspapers, as well as some scientific literature, are describing it, i.e. a forthcoming catastrophe. Indeed, as described in the chapters 2 and 3, the resource peak treatment, and the lack of resources in the near future derive from a common misunderstanding between resources and reserves, as well as from a view that does not take into account historical data.

In this respect, with a long-term vision - i.e. hundreds of years and not decades - the need of a balance between the natural and the built environment should be achieved in order to "allow" the human population, and to the Planet itself, to thrive forever. In this sense, within the human ecology debate, only predictions for thousands of years, even dozens of thousands, are meaningful and worthwhile. This assumption, for now, implies to treat the Earth as a closed system, thus, with a zero input of materials from out of the Planet. Surely, in the near future, it will not be possible to "import" a huge amount of materials required for societal prosperity from other planets, even if it is a possibility not to be discarded in a far away future. As explained by G. Hardin (1968) *"Space is no escape"*, eventually, i.e. in hundreds (perhaps thousands?) of years, future technological improvements related to the space industry may undermine this hypothesis. On top of these premises, the only worthwhile question to investigate is how such a balance between resource extraction and regeneration, between carbon dioxide emissions and absorption rate from the atmosphere and hydrosphere can be achieved and how such a dynamic equilibrium can last forever. To answer these questions, the debate about the *Commons* should be the starting point.

The modern debate about the Commons started more than fifty years ago with a very famous article published on *Science* by G. Hardin (1968) and entitled "The Tragedy of the Commons". The article was facing the population growth issue, and the *free-rider* problem. A free rider, roughly speaking, is *"someone who receives a benefit without contributing towards the cost of its production"* (R. Hardin et al., 2003). G. Hardin recognized that the population growth issue and the management of common-pool resources were not simply related to the accountability and to the right to access to the resources but it was deeper. Using his words, indeed *"the population problem has no technical solution; it requires a fundamental extension in morality"*. G. Hardin described the population problem by discussing the example of a pasture open to all where herders may exploit the pasture with an unlimited number of cows. In his opinion, keeping a common-pool resource (e.g. a finite resource such as a pasture) open to all the ones who can extract resources from the pool, aiming to maximize their gain, inevitably brings to the tragedy of the commons. He wrote:

> *"herein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all."*

Thus, similarly, *"a finite world can support only a finite population"* and population growth should be zero. G. Hardin continued by contrasting the freedom of the family, recognized as the fundamental unit of society by the Universal Declaration of Human Rights, with the limit of common resources: if the family is the fundamental unit, then none can decide about or restrict the number of children and population growth will not reduce to zero. Proceeding on the pollution problem and human density, he argued that *morality is system-sensitive* and moral acts depend on the system and time when they are performed (Fletcher, 1966) rather than on absolute terms. Thus, he concluded that coercive laws were necessary to avoid the tragedy. Although some underlying assumptions in his article were wrong, as the hypothesis to an open to all pool of resources, G. Hardin put the basis of the modern debate about the Commons, and he already envisioned the need of a *mutual coercion*, and not an absolute one, recognized directly by the people affected. Following Hardin's article, in the Eighties the debate emerged again answering to his unsolved questions. In 1986, C. Rose (1986) in "The comedy of the commons: custom, commerce, and inherently public property" argued that not all properties fall into the dichotomy of private and public property, but there is a *"distinct class of inherently public property which is fully controlled by neither government nor private agents"* (p.720). In this sense, C. Rose described some resources, such as social activities, under which the access and the increasing number of participants/appropriators is considered an advantage and not an issue. For such common resources, using her words (p.768), *the more the merrier* is the basic rule. From this consideration, thus, the comedy of the commons rather than their tragedy. Beyond the differences between limited common-pool resources discussed by Hardin and the ones described by C. Rose, her work pointed out the fundamental questions on the management of the commons. In this sense, the most important work was written a few years later by Ostrom (1990), who won the Nobel prize for economics in 2009 for her work on the Commons' governance. In her *Governing the Commons* book, the answer to the unsolved question of the "The Tragedy of the Commons" was figured out. Ostrom (1990) analysed and studied in detail dozens of different common-pool resource systems, which have been managed by local communities. The self-government and the rules defined *mutually* by the appropriators of the resources ensured the long-term preservation of the common-pool resource (CPR). In particular, she identified several common management rules in all the studied CPR ecosystem such as a clear definition of boundaries and of who can access the CPR, who should monitor the access and, in case, punish the free-rider, or the mutually definition of sanctions, were identified as fundamental requirements for a long-enduring CPR. One of the rules to manage a CPR was the self-management by the community of appropriators itself. For further details on the identified principles, see the focus 4.4. By the way, Ostrom run several social experiments to test her assumptions, identifying a perfect communication among appropriators, and a transparent decision-making process, as a fundamental requirement for a long-enduring CPR. Indeed, she discovered that if the engaged actors were not able to communicate among themselves, they always over-exploit the CPR (Rifkin, 2015, p.196).

Focus 4.4 — Commons' principles. Ostrom (1990) in her book *Governing the Commons* put the basic and fundamental design principles for a *long-enduring CPR institution*. After years of studies she identified seven main design principles (Ostrom, 1990, p.90-102):

1. *clearly defined boundaries* must be defined to regulate who, and who not, have the right to access and use the CPR, as well as what are the boundaries of the CPR itself. According to her words (p.91) *without defining the boundaries of the CPR and closing it to "outsiders", local appropriators face the risk that any benefits they produce by their efforts will be reaped by others who have not contributed to those efforts*.
2. *congruence between appropriation and provision rules and local conditions*, which means to set proper conditions about time, place, technology, and/or the amount of resources which can be used, as well as the required labor, material or capital investment.
3. *collective-choice arrangements*, i.e. everyone belonging to the defined boundaries must be allowed to participate in adapting the rules democratically.
4. *monitoring* activities, held by *monitors*, should be directly run by the appropriators or accountable to the appropriators.
5. *graduated sanctions* should be inflicted to appropriators who violate the adopted rules directly by other appropriators or by officials accountable to the appropriators.
6. *conflict-resolution mechanisms*, with rapid access and at low-cost, are required to mediate for any violation among appropriators and officials.
7. *minimal recognition of rights to organize* to the Commons association by external authorities, institutions or governments.

A last final design principle, i.e. *nested enterprises*, has been identified for such CPRs within larger system. In this case, rules defined only at one level, and not in multiple layers of nested systems, generate an *incomplete* system which cannot last long.

Ostrom design principles were as innovative as simple, completely changing past discussions about private and public properties. Indeed, the central and fundamental concept was to move the responsibility of legislating, ruling, monitoring and sanctioning from an external apparently *"super-partes"* actor (e.g. a government) to the appropriators, officials, and participants themselves. As directly stated by Ostrom (1990, p.99):

> *When CPR appropriators design their own operational rules (design principle 3) to be enforced by individuals who are local appropriators or are accountable to them (design principle 4), using graduated sanctions (design principle 5) that define who has rights to withdraw units from the CPR (design principle 1) and that effectively restrict appropriation activities, given local conditions (design principle 2), the commitment and monitoring problem are solved in an interrelated manner.*

In such a governance, thus, the typical debate on sanctions, the *free-rider* problems, and other issues related to cooperative and non-cooperative games, was definitely solved with a *self-regulating* governance and system. The proposed design principles were also studied and tested in laboratories and controlled environments by Ostrom and her colleagues, revealing further insights. A transparent communication was observed to be necessary to set up a Commons around a CPR; indeed, when participants took decision without communicating with each others, the CPRs always were over-exploited (Rifkin, 2015, p.196).

The debate on management models and on strengths and weaknesses of a purely public management, a private one or the Commons is far from being closed. Indeed, which model is better under which conditions and context is still open to debate, and, in general, has no unique answer. ■

Concluding this chapter, how may such considerations on CPRs be applied to an emerging environmental governance, to avoid the Tragedy of the Commons? Assuming that population will not grow forever, as modern population model highlighted, and that raw resources, at least in the short term, will not disappear, what is the most urgent issue to focus on within the current environmental debate? A long-enduring CPR, where long-enduring has to be intended as an *indefinitely-last* CPR, should be managed according to the Commons' principles defined by Ostrom. What should be the focus of a global environmental governance of the Commons? The extraction of available resources? The generated environmental impacts as the carbon dioxide emissions? To answer such questions, several requirements are needed.

First, as pointed out by the laboratory experiments run by Ostrom, a perfect communication among affected people and appropriators and a transparent decision-making process is required. Currently, the open data movement has shown the path to follow, which may provide, at least theoretically, a transparent information. In this sense, for instance, the global data about global resources, annually provided by USGS, are not a good example, as they are still provided neither in an open format nor in a completely transparent way.

Second, a requirement not explicitly stated by Ostrom in the seven Commons' principles but necessary for a long-enduring (indefinitely-last) CPR is the balance between the regeneration rate of the resources and the extraction rate due to the use by the appropriators. If for renewable stocks of resources a static, or a dynamic, balance between the two rates is possible with a wise management of the access to the CPR, ensuring an *indefinitely-last* CPR, it is obvious that for a finite non-renewable stock this cannot be guaranteed simply by managing and/or reducing the access to the CPR. This apparently obvious feature, if projected indefinitely in the future, it is not so obvious. Indeed, even if the extraction rate is reduced at minimum, it is straightforward that a non-renewable finite stock will finish. This can happen in decades, hundreds of years, or even thousands of years, but it will end. There is no other logic and possible end. The only solution could be to find another source of resources or to flow indefinitely the resources already extracted. Assuming that global resources may satisfy the current needs (e.g. housing, energy, care, ...) for all the global population, this is true indefinitely in the future if and only if the in-use stock will last forever, scenario allowed only by recovering every in-use raw material through repairing and reusing products, or recycling the materials. Thus, by using Ostrom terminology, the common-pool resource to be mutually managed should not refer only to the natural stock of resources but to the in-use stock of materials, i.e all the materials within products, buildings, and infrastructures, for instance. For this purpose, in my opinion, a *Circular Commons* needs to be defined[1]. A Circular Commons should follow the Commons' principle as stated by Ostrom but it refers to every product in the market. The ownership itself of products, their management and end of life, should be revised, since the common-pool of resources focuses on the products themselves. In this sense, a step towards the overcoming of the ownership of products and goods has been largely recently (in the last decades) introduced by the collaborative and performance economy (Walter R. Stahel, 2010) and by the sharing economy (Ritter et al., 2019). Both concepts put the basis for new business models in order to move from the production of goods and commodities to the product-as-a-service (Tukker, 2004), where *accessibility* become crucial and more important than the ownership of a good itself (this aspect will be discussed in more detail in next chapter in section 5.3).

Third, as discussed previously in chapters 2 and 3, the boundaries of a Circular Commons should not refer only to the in-use materials within products but it also needs to take into account their environmental impact, in terms of embodied carbon, energy or of other environmental indicators such as the ones discussed by Raworth (2017) as planetary boundaries. Complete life cycle analysis of products should include both upstream - exploration, discovery, production - and downstream - manufacturing, recycling, disposal - processes.

Fourth, how can such a transition towards a new governance can be induced and pro-

[1]The term *Circular Commons* currently has been only used by Franquesa et al. (2016) to define an IT platform (`https://www.ereuse.org/`) for electric and electronic equipment in the city of Barcelona in order to enable a long-enduring CPR for digital devices. The platform, built taking into account Ostrom (1990) principles, provides an open source software to enable global traceability and transparency to reduce e-waste.

moted? Obviously, no unique answer exists. Following the discussion of Ostrom (1990) in order to self-manage a CPR, a top-down coercive power should be avoided. Recently, indeed, policy and decision-makers are promoting incentives or penalties policies, rather than strict regulations, to stimulate new sustainable lifestyles or a behavioural change for citizens. Such approach was originally proposed by Thaler et al. (2008) in their books *Nudge. Improving Decisions About Health, Wealth, and Happiness*. The *Nudge Theory* relies on the definition of Nudge Thaler et al. (2008, p.6)

Definition 4.2.1 — Nudge. A nudge, as we will use the term, is any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives. To count as a mere nudge, the intervention must be easy and cheap to avoid. Nudges are not mandates. Putting fruit at eye level counts as a nudge. Banning junk food does not.

Thus, the *Nudge Theory* has been also defined as libertarian paternalism since it attempts to influence consumers behaviour without coercion (p.5).

Last but not least, assuming a perfect information about in-use materials, their amounts and impacts, a mutual governance made by appropriators, monitors and, more in general by all affected people, necessary conditions for the management of a long-enduring CPR according to the Commons' principles of Ostrom (1990), other relevant and technical aspects and issues should be faced. What are the main properties a Circular object needs? Under which rules and constraints is a circular object defined? Are there recognized technical and design criteria to ensure a material to be perfectly recoverable allowing it to enter within an eternal cycle? These, and many other questions, should be first addressed in order to define precise and mutually recognized criteria and principles every object and product should fulfill. Thus, an indefinitely-last CPR, i.e. a Circular Commons, should be based on precise product design principles.

4.2.3 Towards a circular management.

In the past decades, several methodologies and approaches have been proposed to evaluate the potential of material recycling within a product. For instance, since the Nineties the Sherwood plot, generally used to evaluate the feasibility of materials' extraction in the mining industry, has been proposed as a graphical tool to evaluate the recycling potential of products (J. Johnson et al., 2007) and material waste streams (Allen et al., 1994). The Sherwood plot, i.e. the logarithm plot of materials concentration vs the material price per kilogram, indeed, may be a good estimator to assess the profitability of recycling certain materials or not, simply by analysing their concentration within a product, and their market price. Similarly to the Sherwood plot, Dahmus et al. (2007) discussed a better estimator by computing the *mixing entropy* as an indicator of product complexity and, thus, of recycling potential. Figure 4.6 shows the resulting plot (adapted from the original plot presented in 2007) where the x-axis represents the mixing entropy H (in bits) and the y-axis the recycled material value of a single product (in a logarithmic scale). Basically, what they found was a concept previously and largely debated by designers, in particular by the sub-fields of Design for Disassembly (DfD) and for Recycling (DfR), about complexity and recoverability of materials and sub-components within products. In general, the larger the entropy, the higher the complexity of a product, and thus the lower the material, or component, recovering potential. For further details on product complexity, see the focus 4.5.

In the next chapters, before we focus on precise design criteria and fundamental methodological aspects to enable the circularity of products, the emerging new paradigm of the Circular Economy will be introduced and discussed, from a theoretical (chapter 5), historical (chapter 6), and methodological point of view (chapter 7). In particular, in chapter 5 basic concepts will be discussed, from new emerging business models to the regenerative design concept and the 10R framework, in order to give a preliminary and general overview necessary to introduce the circular economy. The chapter ends describing the fundamental questions to design a theory in the framework of the Information System Design Theory (ISDT). In chapter 6, the underlying concepts and schools of thought behind the circular economy are briefly summarized and an analysis on thousands of Wikipedia webpages is presented to discuss if, currently, the Circular Economy could be considered as a new emerging paradigm or just a relabelling of old knowledge. Finally, in chapter 7 the fundamental tools and methodologies adopted by academics and practitioners in the field of environmental assessment and circularity are described, highlighting pros and cons, as well as relevant examples.

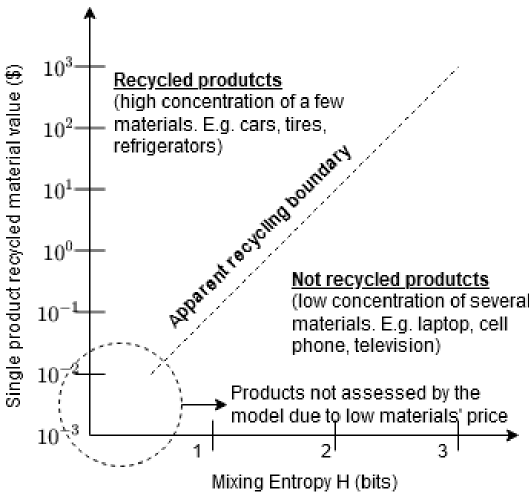


Figure 4.6: Apparent recycling boundary. Mixing Entropy versus value of recycled material in a product. Adapted from Dahmus et al. (2007)

Focus 4.5 — Product complexity. The link between product and material, complexity and the recovering potential traces back to the Fifties. One of the first model to assess the materials' extraction feasibility by the mining companies was the so-called Sherwood plot, i.e. the materials price versus the logarithm of materials' concentration (Allen et al., 1994; Grübler, 2003). The studies on materials' concentration and profitability generally showed that the value k_i of material i, expressed in dollar per kilogram, is linear with respect to its dilution $^1/_{c_i}$. c_i is the concentration of the material i with respect to the total mass of the extracted material. The rationale is trivial. The higher concentration, the lower the cost of extraction (for the same amount of pure material), and, thus, the higher the profitability. The Sherwood plot related the concentration to the profitability according to

$$k_i m_{mix} c_i > k_{mix} m_{mix} \tag{4.2}$$

where k_{mix} is the total cost to process the total mass of the mixture containing the target material, and m_{mix} the mass of the mixture.

Recently, inspired by the Sherwood plot, several academics proposed their assessment model based on the number of materials (B. H. Lee et al., 1997; C. M. Rose, Kosuke Ishii, and Masui, 1998), the mixing entropy (Dahmus et al., 2007), or the number of binary steps required to extract a material from a product (Sodhi et al., 1999). In particular, the Shannon entropy was described originally in 1948 by Shannon (1948) in Information Theory as a measure of the information contained in a message. In terms of concentration of materials, as described by Gutowski et al. (2005), it can be defined as:

$$H = -K \sum_{i=1}^{M} c_i \log c_i \tag{4.3}$$

where H is the total entropy of a product, K is a constant (by convention equal to 1), M is the number of materials within the analyzed product and c_i is the concentration of material i over the total weight. c_i expresses the probability to find a certain material within a product, such that $\sum_i^M c_i = 1$. The advantage to use the entropy as a complexity measurement lies on theorems and relationships previously developed in Information Theory and mathematics. Indeed, the mixing entropy includes both the number of materials, their concentration and the number of steps to extract a material within a product (Dahmus et al., 2007; Gutowski et al., 2005). By defining the average number of steps to extract a material $\overline{n}$ as:

$$\overline{n} = \sum_{i=1}^{M} c_i n_i \tag{4.4}$$

where n_i is the number of steps required to extract the material i, thanks to the Shannon's Noiseless Coding Theorem, it is possible to show that the entropy is a lower boundary of the average number of steps according to

$$\overline{n} \geq \frac{H}{D} \tag{4.5}$$

where D represents the processes to separate the materials (Gutowski et al., 2005). ■

Part Two.
Background

5. An emerging paradigm

The Collaborative Commons
is already changing the way
we organize economic life,
offering the possibility of dramatically
narrowing the income divide,
democratizing the global economy,
and creating a more ecologically
sustainable society.

Jeremy Rifkin

Paradigm, in the meaning exposed by T. S. Kuhn (2009) in his groundbreaking book *The structure of scientific revolutions* in 1962, refers to new scientific discoveries able to move forward science towards a new epoch. According to him, a scientific paradigm has two main general characteristics: the new results are able to attract a stable group of followers, and are sufficiently open to allow scientists to solve problems of any kind with the new introduced scientific "lens". In such a way, T. S. Kuhn described some of the fundamental scientific historical books such as the *Physica* of Aristotle, *Principia* and *Opticks* of Newton, *Chemistry* of Lavoisier and *Geology* of Lyell, just to name a few. In Kuhn's opinion, science is divided into the so-defined *normal science*, and the *extraordinary science*. The normal science refers to *"research firmly based upon one or more past scientific achievements"* (T. S. Kuhn, 2009, p.29), while the extraordinary science focuses on the emergence of new paradigms when a crisis, in previous theories, occurs. A scientific crisis starts to emerge when new technologies, or new discoveries, undermine the integrity of the current theory through new experimental results, or the increasing awareness about the failure of a model. New paradigms emerge as an answer to the lack of explanations at some physical questions, and the extraordinary science, will first try to isolate the failures, then it will question and investigate more deeply the identified theoretical failures. It is exactly at this point, that the scientists will turn *to philosophical analysis as a device for unlocking the riddles of their field* (T. S. Kuhn, 2009, p.115) and the new paradigms emerge, as an *extraordinary science* achievement.

Similarly, nowadays social and economic theories and models are deeply criticised and questioned. The failure of our current economic model is unquestionable. Scientists and academics from all fields strongly criticized the oversimplified linear model of production, and more deeply the capitalist economic system of growth. According to Rifkin (2015, p.12) the capitalistic paradigm is *now under siege on two fronts*.

First, as pointed out in past decades primarily by environmental economics, the neo-classical economic theory, built up on the same rationale of Newtonian physics (Raworth, 2017), is nowadays challenged by a new economic view based on the laws of thermodynamics. Indeed, from the first historical works of Boulding (1966), Daly (1974), or E. P. Odum et al. (1971), environmental economics, and its evolution, is grounded on the conservation of energy and mass, or on the increasing of entropy. Classical economists fail to take into account the conservation of energy (1st law of thermodynamics) and the continually increasing of entropy in the universe (2nd law). Indeed, according to the second-law of thermodynamics, entropy always increases in every irreversible (i.e. real) process. Similarly, in more recent years, the term *exergy* (from Greek, ex“ex”, external, and “ergos”, work) was coined by Zoran Rant in 1953 (Koroneos et al., 2012) as the maximum useful work during a process when a system moves towards the equilibrium with the environment (Goran Wall et al., 1986), representing a measure of the quality of energy. Similarly to entropy, in each irreversible real process, exergy decreases (the reverse of entropy that is a constantly increasing state variable). Since the Earth is a *spaceship economy* (Boulding, 1966), i.e. a closed system with no exchanges of matter and only a constant energy input from the sun, the economy, according to its original Greek meaning, Oeconomicus (from oikos, house, and nomos, law or rule) (Cameron, 2008), should focus on the wise management of our house, the Earth. Thus, all economic activities, which, in thermodynamical terms, are simply irreversible transformations of energy from one state (e.g, raw materials) to another (e.g. a finite product) should have been evaluated in such terms. But it has not. Using the words of Rifkin (2015, p.13), the *“entropic bill for the Industrial Age has arrived.”*. However, the current human challenge cannot only be reduced to an energetic, or an entropic, challenge. The planet boundaries must be respected to live in the so-called *safe and just space* by considering all the nine categories[1] described by Raworth (2017) in the book *Doughnut Economics: seven ways to think like a 21st century economist*.

[1]Ecological ceiling: climate change, ocean acidification, chemical pollution, nitrogen & phosphorous loading, freshwater withdrawals, land conversion, biodiversity loss, air pollution, and ozone layer depletion

Second, the emergence of new disruptive technologies within the communication / energy / transportation matrix is boosting the so-called *Third Industrial Revolution*. In particular, according to Rifkin (2015), the Internet of Things, the internet-based communication, and new production processes (e.g. renewable energy, and 3D printer) are drastically and suddenly dropping the costs of communicating between people and of producing energy and products towards a *zero marginal cost society*. This collapse of production costs, following Rifkin discussion, will permit the emerging of the *Collaborative Commons*. Commons, as previously described, are typically found in local rural communities with common resources, where decisions regarding the "pool" are taken democratically. The Commons has been pointed out by Ostrom (1990) to be a successful governing model, although generally on a small scale, and Rifkin (2015, p.20) defined it the *early archetypes of today's circular economy*. The cost reduction for production reduces the entry costs for new peer-to-peer businesses, allowing to create and share information, as well as energy, goods and services for everyone. Meanwhile, within the circular economy paradigm, ownership is gradually transitioning towards a pay-per-use, or a product-as-a service, approach, boosting the shift towards the Collaborative Commons where access is becoming more important than the ownership itself. The emergence of the new Collaborative Commons paradigm, as pointed out by Rifkin (2015, p.23), is also highlighted by the use of the word collaborative, which appeared only in the 1940-50s, and, later on, it commonly spread thanks to the diffusion of computers and of the peer-to-peer culture.

On top of these discussions, apparently very far apart, on energy and resource management, the Circular Economy, as a new concept, is moving its first steps. As a new young baby, before becoming adult, it will inherit the parents' culture by mixing their teaching with the chaotic influence of the outdoor world. The circular economy, in my opinion, is not yet mature since a strong theoretical background is missing. In other words, following the discussion of Rifkin (2015), Ostrom (1990), G. Hardin (1968) and many others, as it is defined nowadays, does the circular economy rely on private market, public government, or on the Commons? What future does it envision? A future where resources, land and the air itself belong to private investors and capitalists who may "circular" wash their own businesses, similarly to green washing practices, or to a global Commons, a collaborative management of our planet? What will be the future management of our planet Earth? Will it be based on the neoclassical economics now in crisis or in a new emerging paradigm, such as the Collaborative Commons proposed by Rifkin (2015) or on another one not discussed yet? The Circular Economy might, or might not, be the answer to face the future management depending on the path it will take in the coming years. The premises to candidate the circular economy as a new paradigm are robust and promising but, currently, not sufficient. As occurred in the past with emerging innovative business models which promised a completely change in route (e.g. the sharing economy), the circular economy might be simply absorbed by the current economic system and only slightly modify it. On the contrary, the introduction of the circular economy, if not simply considered as a way to stimulate and boost the recycling, reuse, or repairing, might undermine the foundation of the current economic model, giving to the critics of the eternal growth assumption a hope and a new path to follow. Unfortunately, there is no simple answer to these questions. To properly discuss the role of the circular economy in the current economics theory and in the management of our society, the first step is to define what, actually, the circular economy (CE) is. In this chapter, the basic concepts of CE, new circular business models and how to design a theory are discussed in order to introduce the next chapters where the schools of thought, methodologies and concepts behind the CE will be treated in more details.

The rest of the chapter is structured as follows. Starting from a theoretical and philosophical background, in section 5.1 the necessary transition from a sustainable to a regenerative economy and society is discussed. Moving from the sustainable development paradigm, which, in my opinion, still lies within the classical economic paradigm, to the regenerative concept is essentially the first step to plan our lives within the planetary boundaries. Consequently the shift from the linear to the circular model, necessary for a successful transition towards the Collaborative Commons, is treated in section 5.2 by introducing the basic concepts and fundamentals of the Circular Economy; then, in section 5.3 the main circular business model archetypes, their risks, barriers, and opportunities are presented, in order to provide a pragmatical preliminary overview. A case study regarding single-use vs reusable plastic cups is also reported in detail. Finally, in section 5.5, a theoretical discussion on how to design a theory introduces the relevant open research questions this thesis attempts to address.

5.1 From sustainable to regenerative

Another world is not only possible,
she is already on her way.
In quiet days I can hear her breathing.

Arundhati Roy

This section is partly based on *Easy Open Data* (Dario Cottafava, 2018), on “Education of sustainable development goals through students’ active engagement” (Dario Cottafava, Cavagliá, et al., 2019) and on the book contribution “Big Data, social networks, and well-being” (Dario Cottafava, 2020) in the book *Regenerative design in digital pracice. A handbook for the built environment* (Naboni and Havinga, 2020).

The origin of the concept of sustainable development traces back to 1987, when the World Commission on Environment and Development released the Brundtland report - also known as the “Our Common Future” (Brundtland et al., 1987) - where it was defined as:

> **Definition 5.1.1 — Sustainable development.** Development that meets the needs of the present without compromising the ability of future generations to meet their needs.

With this powerful statement, the Brundtland report established the foundation for the indivisible interconnections between the economy, society and the environment. This concept has been developed in many theories, exploited with many different approaches and redefined in several other fields as the Triple Bottom Line (TPL), term coined by John Elkington in 1994 (Elkington, 1994). The concept of a sustainable development evolved and spread worldwide during the last decades, especially during the last fifteen years, thanks to policies adopted by UN and UNESCO. However, the powerful theoretical framework of the sustainable development, set up in the eighties by Brundtland et al., has been widely debated. If, on one side, the reduction of the environmental impact of human activities is the main driver for products, or processes, design and the implementation of new policies, on the other side, the sustainable development definition is still based on an anthropocentric point of view. In the same years of the Brundtland report another powerful concept was emerging. According to the Deep Ecology ethics (Singer, 2011) - *the development would not be right if the ecosystem is significantly affected by it* - rights and duties must also be prescribed to smarter animals (Watson, 1979), sentient beings (Warnock, 1971), living beings (Goodpaster, 1978), and *beings in existence* (W. M. Hunt, 1980).

To understand well the two points of view, let me discuss an analogy with psychology theory. According to Gallino (1997), in psychology theory people behave according to two main principles, i.e. identification and individuation. The former refers to the assimilation process of individuals from the surrounding environment (Ferraris et al., 2018, p. 127-130), while the latter, in Jungian psychology (Jacoby, 2016; Kelly, 1993), represents the psychological process of self-development of the individuals by separating and distinguishing themselves from the surrounding. More in general, the individuation process focuses on the separation of a *thing* from *other things* (Humphreys et al., 1997). Taking into account these definitions and psychological processes, the anthropocentric viewpoint can be seen as a consequence of a prevailing individuation process rather than an identification one. On the other hand, in philosophy, the shift from an ego-centric to an eco-centric life is well-explained and discussed within the Posthuman thought (Braidotti, 2013). According to the posthuman theory, no rigid boundaries among humans, animals, machines, and nature exist where the new recognized *subject* is the collective Nature (Braidotti, 2013). For further details see focus 5.1. In other words, according to Eisenstein (2013), a shift is needed from a *story of separation* where people are isolated from Nature, to a *story of interbeing* focused on the interdependence with nature. With his words, the path from the sustainable approach towards the regenerative one is a shift from a *world of less* to a *world of more*:

> *we are offering people not a world of less, not a world of sacrifice, not a world where you are just going to have to enjoy less and suffer more - no, we are offering a world of more beauty, more joy, more connection, more love, more fulfilment, more exuberance, more leisure, more music, more dancing, and more celebration.*

Focus 5.1 — Sustainable development in philosophy. Posthuman is a word emerged from science fictions in the nineties and adopted and analysed by contemporary art and philosophy in the past two decades. Literally it represents the state, for a human, beyond the human being state itself. Posthumanism varies from other anthropocentric theories, as the transhumanism, for instance, where there is no radical change in the *subject* but only an enhancement of human beings due to the nanobiotechnology. The origin of the posthuman theory can be attributed to Donna Haraway who wrote in 1984 “A cyborg manifesto: Science, technology, and socialist-feminism in the late 20th century” (Haraway, 2006) and defined a rough synonymous with the word cyborg. Posthuman, in its first meaning and definition of cyborg, referred to the rejection of the rigid boundaries and borders among humans, animals, machines and nature. As Haraway (2006) wrote, *“the cyborg would not recognize the Garden of Eden; it is not made of mud and cannot dream of returning to dust”*. Donna Haraway, thanks to the cyborg metaphor, criticizes the traditional approach of feminism based on the identity, highlighting differences instead of the coalition through affinity. A Cyborg Manifesto, in this way, set the basis of the posthuman theory and for critical philosophers of the subject. In fact, in the posthuman a new ontology of the subject emerges, where individual is no longer defined as a stand-alone entity but its definition depends on the surrounding world from a heterogeneous and partial perspective instead of an absolute moral truth (Haraway, 1988). Beyond Haraway, Hayles, exploring the complex interaction between human and environment in the late 20th and 21st centuries due to the explosion of the Information Technologies, argued the liberal humanism definition of mind-body in order to overcome the classical dicotomy (Hayles, 2008).

The discussion on a posthuman theory evolved in particular thanks to Braidotti (2013), an italian philosopher and Professor at the University of Utrecht, who postulated the necessity of three main elements for the posthuman theory: 1) the development of new subjectivities, 2) the embracing of a posthuman ethics and 3) the construction of an affirmative posthumanist politics. All three elements will be required for the vision of a sustainable futures in order to overcome anti-humanism. In Braidotti opinion, in fact, the crisis of the anthropos and of the anthopocentric world is exploding in recent years due to global challenges as the climate change, the preservation of the biodiversity and other environmental global issues and, in order to face these challenges, we have to *“embrace the risks of becoming-other-than-human”*. A positive life force is needed, and a new ethics may be founded, as a new approach for a global politics. Braidotti defined the *“life beyond death”*, the life-death continuum, the zoe-life beyond the anthropocentric point of view which frees us in a completely new unexplored territory. The posthuman, in this sense, is a process of redefining the interconnection with the world and the environment: from a local and urban scale up to a planetary scale, the social, psychic and ecological aspects will be redefined, recognizing the collective nature as a new subject. The new subject becomes a mobile assemblage in a shared living space: the new subject cannot anymore control the surrounding space, as in liberal humanism, but simply it lies in it, acting in communities, groups or networks. Thus, for the post-human theory the subject is a transversal entity fully immersed in a network of non-human relationships (Braidotti, 2013). Using the words of Braidotti (2013), *“not all of us can say, with any degree of certainty, that we have always been human, or that we are only that”*.

Posthuman brings us to overcome the anthropocentric view of life, the myth of

> one humanity based on universal values. In this sense, feminism and other right movements (e.g. gender, race, class, culture, nation) have already demonstrated us that the human definition has always been negotiable. Thus, Braidotti argues that posthuman is a freedom force which set every subject, humans, animals, nature, even AI, at the same level, and it will help to imagine a new global ethics. ■

The same distinction appears for the definitions of *eco-efficiency* and *eco-effectiveness*. An eco-efficient strategy aims to minimize the environmental impacts or the usage of raw materials, and in the meanwhile to maximize the economic profit of the human activity (Verfaillie et al., 2000). The eco-efficiency concept, first appeared in the seventies as environmental efficiency and later defined as the *"business link to sustainable development"* (Schaltegger et al., 1990), still lies into the linear economic paradigm (Braungart et al., 2007). In few words, eco-efficiency simply tends to decouple environmental impacts from economic benefit. On the contrary, the eco-effectiveness approach aims to transform waste, products' scraps, and any material flow into supportive and useful parts for the natural and artificial ecosystems in order to recoupling economic and environmental benefits (Braungart et al., 2007). Similarly, according to M. Brown (2016), the new paradigm, for the built environment, recently converged into the Sustainable-Restorative-Regenerative shift. *Sustainable* represents the outdated view, i.e. the anthropocentric viewpoint focused on limiting the environmental negative impacts on the ecosystem. *Restorative* design highlights an approach to restore eco-, social and economic systems to a healthy state, while the new paradigm is represented by the *Regenerative* approach where ecological, social and economic co-benefits are enabled. Thus, regenerative design attempts to move beyond the sustainability paradigm of *"doing less bad"*, and even farther than restorative design, whose main aim is to restore healthy ecosystems (Wahl, 2016, p. 46-47). Regenerative design focuses on virtuous reinforcing feedback loops able to restore local ecosystem and to maintain them in balance (Reed, 2007).

5.2 From linear to circular

The concept of the circular economy is grounded in the study of non-linear, particular living systems. A major outcome of taking insights from living systems is the notion of optimising systems rather than components.

Ellen MacArthur Foundation (Wahl, 2016)

The text of this section is partly based on and adapted from the contribution "From flow to stock. New Circular Business Models for integrated systems: a case study on reusable plastic cups" (Dario Cottafava, Riccardo, et al., 2019) presented at the *"23rd International Trade Fair of Material & Energy Recovery and Sustainable Development, ECOMONDO"* held the 5th-8th November 2019 in Rimini, Italy.

The CE has emerged in past decades as the overcoming of the current economic paradigm based on the linear flow of resources from the raw materials extraction to the disposal of the produced waste. The CE aims to *"gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system"* (Ellen MacArthur Foundation, 2017). Regenerative and restorative by intention, it relies on three main principles: 1) design out of waste and pollution, 2) keep products and materials in use, and 3) regenerate natural systems. In general terms, according to the Ellen MacArthur Foundation as cited by CIRAIG (2015), the circular economy relies on five core principles:

1. **systems thinking**,
2. **waste is food**
3. **design out of waste**
4. **diversity is strength**
5. **renewable energy**.

A CE system should be a highly interconnected (*systems thinking*) economic system, or a supply chain by thinking more specifically, where there are no waste (*design out of waste*) or each waste flow is used as input for other processes (*waste is food*). The redundancy, as in nature, and the diversity of engaged actors should be empowered as much as possible (*diversity is strength*), and the whole system/supply chain should be powered only by the use of *renewable energy*. Hence, besides the most straightforward principles of reducing waste production and increasing the production of energy from renewable sources, Circular Economy is also deeply tied to the resilience and adaptation of an ecosystem (diversity is strength principle) and a circular product or business cannot be fully understood without taking a holistic and systemic vision (system thinking principle). See Focus 5.2 for a brief introduction about resilience and adaptation.

Focus 5.2 — Resilience and adaptation. Resilience has been declared the 2013 buzzword (Time, 2013). The academic debate about resilience gained its momementum in the last decades due to the dozens, hundreds of natural disasters we are experiencing every year, although the resiliency of an ecosystem is studied since decades in ecology (Harrison, 1979). In particular, during the Rio+20 conference on sustainable development the term resilience fully entered in the public and political debate. Originally introduced in the Sixties, resilience has been studied in several research fields, from mathematics to ecology, from engineering to complex system and psychology. It refers to the ability to *bounce-back* after a change of a system (K. Brown, 2014). According to Nelson et al. (2007) resilience can be defined as:

Definition 5.2.1 — Resilience. The amount of change a system can undergo and still retain the same function and structure while maintaining options to develop.

The *"bounce-back"* resilience, in the literature commonly named *engineering resilience*, refers to the property of a system to quickly return back to its original state (Marchese et al., 2018). Broader definitions from the ecological school of thought assume that multiple stable states exist and that a system can transit from one to another one. Thus, according to NAP (2012) ecological resilience is:

Definition 5.2.2 — Ecological Resilience. The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.

Although the differences in definitions, the resiliency is a property of an entire system, not of a single part or component. As mentioned above, a few concepts are crucial to plan a resilient ecosystem: multiple states, adaptive capacity, and governance. Multiple states is a basic property of complex systems (e.g. the natural ecosystem) which implies that multiple stable states exist (Berkes et al., 2008) and hence a resilient system could change state instead of simply bouncing back to the original equilibrium. Consequently, a resilient strategy should point to *desirable states* when the *threshold* of the original state is crossed. Thus, *Adaptive Capacity* represents the requirements to move towards another desirable states or, as defined by Berkes et al.:

Definition 5.2.3 — Adaptive Capacity. The preconditions necessary to enable adaptation, including social and physical elements, and the ability to mobilize these elements.

Generally speaking, adaptation is the process necessary to cope with changes:

Definition 5.2.4 — Adaptation. The decision-making process and the set of actions undertaken to maintain the capacity to deal with current or future predicted change.

Hence, to stimulate adaptation of an ecosystem a long-enduring governance is necessary to persist to different transitions between two desirable states. Cumming et al. (2006) argued how *"community self-organisation"*, comanagement and decentralized governance are necessary to manage a resilient ecosystem. Finally, both resilience and adapation strategies need to generally target system vulnerability, i.e. *the susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt*. ■

The CE can be simply illustrated thank to the butterfly diagram (Figure 5.1) as two parallel and interconnected cycles, i.e. a biological and a technical cycle. The biological cycle represents the material flow of all organic materials which can return to the environment to regenerate local ecosystems or can be used to produce energy through biogas. The technical cycle, instead, refers to all closed loops for products, components or raw materials. Generally, regarding the technical cycle, the inner cycles impact less than the outer ones. For instance, repairing is environmentally better than remanufacturing, or reusing is better than recycling.

In order to facilitate an effective understanding of CE, the current industrial-economic system can be first questioned. The current economic paradigm is designed along a linear sequence of "take-make-use-dispose" (Moreno et al., 2016), based on the exploitation of natural resources (exhaustible) and on the dispose of products at the end of life. This model has guaranteed well-being and prosperity until now but has, at the same time, generated relevant impacts both from an environmental and a social point of view. Moreover, in the current (linear) economic model, the exploitation of natural resources

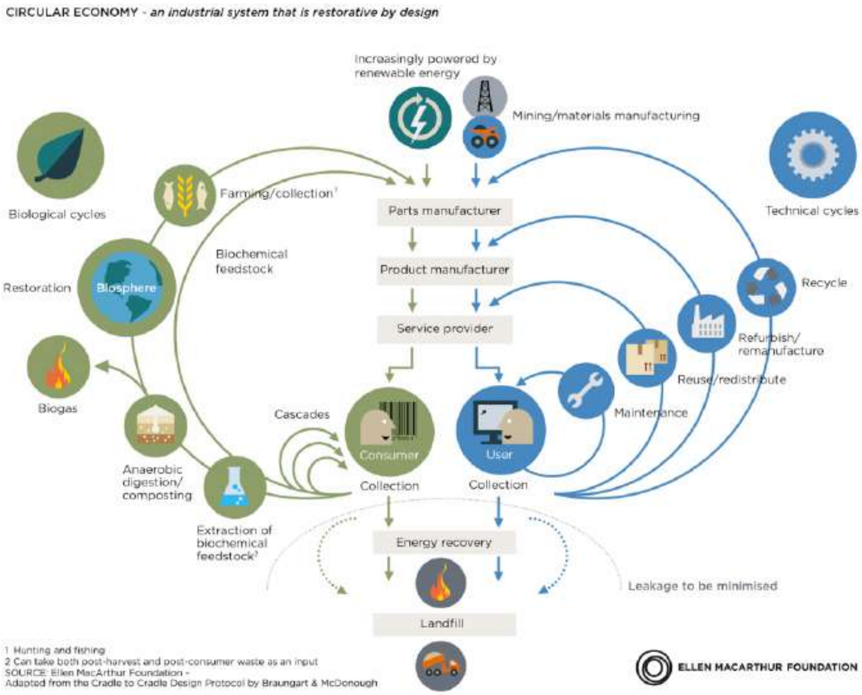


Figure 5.1: Butterfly diagram. Representation of biological and technical cycles. Source: Ellen MacArthur Foundation (2017).

to drive economic activities leads to more than 11bn tons of waste annually worldwide and over 50% of Greenhouse gas emissions are related to virgin materials management activities - extraction, manufacturing, transportation and disposal (OECD, 2018). On average, Europeans are consuming materials and resources at twice the speed the Planet can regenerate them (EEB, 2017); as a consequence, resources are becoming more expensive, due to their scarcity, and raw materials extraction is constantly becoming less sustainable (FAO, 2011; Paquot, 2017). In this context, businesses across the world are dealing with several risks, such as raw materials price volatility, scarcity of resources and new consumer behaviours. On the contrary, a different economic paradigm, such as the Circular Economy, can mitigate such risks and create economic opportunities (Ramkumar et al., 2018). A shift in values and purposes is required for the sustainable transition (Bocken, Schuit, et al., 2018; Bocken and Short, 2016; Ehrenfeld et al., 2013). To avoid the negative externalities of the linear system, we cannot just “do less bad”, a re-design on how materials and products are produced is necessary in order to decouple the amount of needed natural resources and the negative impacts from the economic development (EC, 2018).

The “Circular Economy” can be the paradigm to tackle environmental issues while boosting competitiveness of companies (EC, 2018); for businesses, there are multiple ways to implement circular economy principles, depending on the chosen cycle (biological versus technical) and on the inner / outer cycle in which the company's business model operates. As shown in the butterfly diagram of the Ellen MacArthur Foundation (EMF), the main scope is to minimise or, even better, eliminate waste in order to make useless waste-to-energy solutions (e.g. incinerators) and landfills, because every single products is designed to be reused, repaired, remanufactured or recycled. CE directly derives from the industrial ecology (Bocken and Short, 2016). In the 1990s, R. U. Ayres (1994) introduced the idea of industrial metabolisms defining it as an *"integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes"*. More recently, McDonough et al. (2010) highlighted the necessity to close material loops, divided into "technical" and "biological" type, in a "cradle-to-cradle" economy, rather than cradle-to-grave economy. Moreover, Walter R. Stahel (2010) discussed the fundamental difference between recycling and reuse, highlighting the importance of the latter for a circular approach. Especially in the food system, including packaging industry, the CE represents a huge opportunity to reconnect business purposes with social values, leveraging on cities as a catalyst for change. The way we currently produce food, and manage the resulting waste, generates significant negative economic, health, and environmental impacts. If nothing changes, by 2050, the food system will have used two thirds of the remaining global carbon budget to keep the world under $1.5°C$ increase (EMF, 2019).

On top of thesee theoretical definitions about Sustainable Development, Regenerative Design, and Circular Economy, in pragmatic terms how may a circular economy be implemented? What are the main concepts and approaches an entreprise can adopt? In the next section, the novel Circular Business Models will be briefly discussed in order to give an overview on how to put previous general concepts into actions.

5.3 Circular Business Models

Broadly speaking, according to Osterwalder et al. (2010), *"a business model describes the rationale of how an organization creates, delivers, and captures value"*. A business model (BM) is defined as:

> **Definition 5.3.1 — Business Model.** The conceptual and architectural implementation of a business strategy and the foundation for the implementation of business processes (J. E. Richardson, 2005).

Osterwalder et al. in their book *Business model generation: a handbook for visionaries, game changers, and challengers* introduced the worldwide adopted Business Model Canvas (Figure 5.2), a fast tool to analyze an organization business model, identifying 9 main building blocks: 1) customer segments, 2) value propositions, 3) channels, 4) customer relationships, 5) revenue streams, 6) key resources, 7) key activities, 8) key partnerships, and 9) cost structure. The value propositions identify the customers' problems which are addressed by the business and delivered to the customer segments through the chosen channels. The Customer relationships building block focuses on how the different customer segments are maintained through time in order to generate the revenue streams. The revenue streams block highlights how profit is made by delivering successfully the value proposition to customers. The key blocks, i.e resources, activities, and partnerships, point out the necessary assets, activities and external partners required to run a successful business. Finally, the cost structure block reveals which costs (startup, operational, ...) should be incurred. Although the original canvas introduced by Osterwalder et al. focuses mainly on economic aspects, revenue and costs, and on how to generate or incur them, in recent years several canvas have been proposed by researchers and practitioners to address and assess, for instance, the triple bottom line aspects - economic, environmental, and social - of sustainability (Joyce et al., 2016) or the new strategies adopted within the circular economy framework (Lüdeke-Freund et al., 2019).

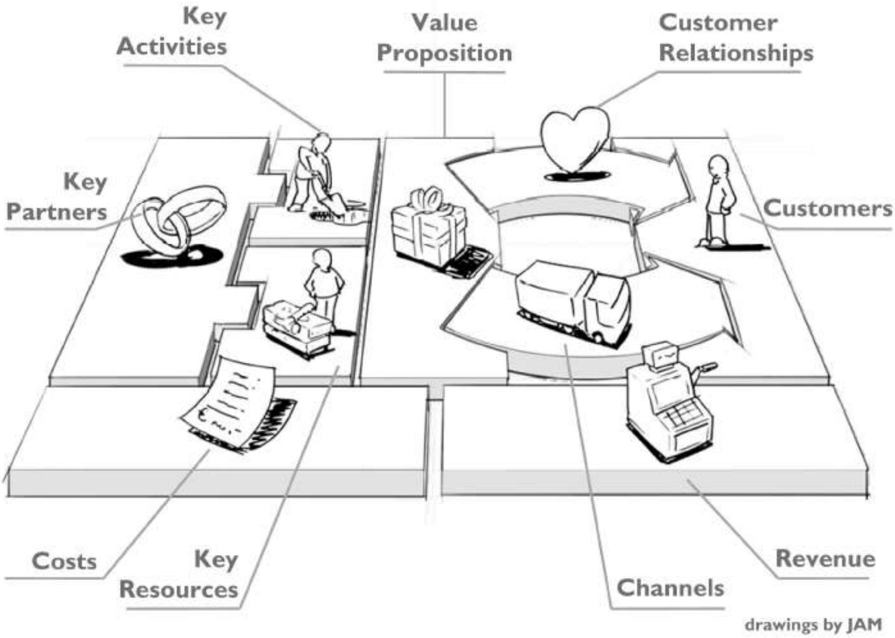


Figure 5.2: Business model canvas. Source: Osterwalder et al. (2010)

Within the linear supply chain framework, business as usual strategies generally focused on extracting raw materials, transforming them into components or products, and, finally, sell the products to consumers and customers. As revenue streams of enterprises, in a linear economy, mainly derive from direct sales, products have been designed for planned obsolescence, and not to last forever, or for a long time. On the contrary, in a circular supply chain, materials are kept in circulation as long as possible and, meanwhile, the utilization rate, i.e. the intensity of use, should be maximized during the entire lifespan of the product (Sariatli, 2017). Thus, it is fundamental to rethink current business models because of the different mechanism underlying value creation. Indeed, from a business model point of view, updating a linear supply chain to a closed-loop supply chains (CLSCs) is not enough, and companies should modify their BM in order to identify new value creation mechanisms within a CLSC (Schenkel et al., 2015). In a circular economy, new business models attempt to slow or to close the resources' loops. Sustainable supply chain management, as defined by Hassini et al. (2012), attempts to *"maximize the supply chain profitability while at the same time minimizing the environmental impacts and maximizing the social well-being"*. Indeed, according to Barquet et al. (2016) a circular business model is defined as:

Definition 5.3.2 — Circular Business Model. The rationale of how an organization creates, delivers and captures value with and within closed material loops.

The sustainable approach, i.e. slowing resource loops BMs, mainly focus on product life extension and on repairing and reusing strategies. In recent years, the sustainable supply chain management has been highly criticized by academics as inadequate to face the planetary boundaries challenge (L. Matthews et al., 2016). On the contrary, closing resource loops BMs aim to completely avoid resource waste (Lüdeke-Freund et al., 2019) by recovering all used materials. According to Bocken, Pauw, et al. (2016), material flows may be narrowed, slowed, and closed. The former two strategies focus on resource efficiency and product lifespan and they don't represent a fully circular approach, while only the latter may be properly attributed to the circular economy. Within the circular economy framework proposed by the EMF (EMF, 2013) six main *reverse cycles* may describe the major strategies:

1. repair & maintenance,
2. reuse & redistribution,
3. refurbishments & remanufacturing,
4. cascading & repurposing,
5. recycling,
6. biochemical feedstock extraction

The first four strategies refer to the technical cycle, while the last two points lie within the biological cycle. *Repair & maintenance* aims to extend the lifespan of products during the use phase, *reuse & redistribution* aims to reuse products with the same purpose their were designed for, while *refurbishments & remanufacturing* strategies focus on update old products directly by the manufacturers in order to renovate them as equivalent new ones. *Recycling* focuses, instead, on recovering the raw materials of products and not the products themselves. *Cascading & repurposing* strategies refer to the reiterative use of energy, materials, or products in the same production process, or in other processes, in order to minimize all possible waste output. Repurposing, in particular, refers to the use of products for other purposes. Finally, *organic feedstock* BMs use the last organic residual of industrial processes for biogas production, composting or anaerobic digestion. Generally, according to Walter R Stahel (2013) a circular business follows five main principles:

1. the smaller the closed loop, the better, environmentally and economically;
2. loops are infinite with no end;
3. managing efficiently the stock depends on the flow speed, the slower the loop, the more efficient;

4. closing the loop by reusing, repairing, or remanufacturing without changing the ownership is economically profitable;
5. *functioning markets* are necessary for circular businesses.

To clarify the different typology of BMs for the circular economy, Lüdeke-Freund et al. (2019) reviewed 26 common circular economy business models (CBMs), and analyzed them with a morphological analysis of design options. Each CBM has different advantages and drawbacks and focus on the production, use or end of life phases. Among others, some common reviewed CBMs are[2] extending product value (Bocken, Pauw, et al., 2016), online waste exchange platform (Albino et al., 2015), recycling and waste management (Kiørboe, 2015), product transformation (Planing, 2015), reuse / refurbish / remanufacturing / next-life sales (Planing, 2015), repair (Kiørboe, 2015), pay per service unit (Tukker, 2004) or product-as-a-service (Tukker, 2004), sharing platform (Taranic et al., 2016), take back management (Bisgaard et al., 2012), and encourage sufficiency (Bocken, Pauw, et al., 2016). Skipping the most straightforward CBMs, several emerging business approaches such as online waste exhange emphasized a collaborative peer-to-peer approach (Hughes et al., 2008; Sundararajan, 2014), while others such as product-as-a-service, pay per service unit, or sharing platform aim at eliminating the consumer ownership of products by substituting with leasing and renting. Take back management, instead, aims to introduce deposit-return system for single-use or reusable products in order to stimulate citizens and consumers, for instance, with benefit and money awards (Dario Cottafava, Riccardo, et al., 2019). Finally, more traditional CBMs such as recycling, remanufacturing, repair, and so on, point to recover products, components, and materials at their end of life. The new business models, as obvious, have many advantages or drawbacks, depending on the adopted strategy. Next paragraph briefly introduces the main challenges, barriers and enablers.

Risks, barriers, and opportunities

Referring to the six main reverse cycles of the EMF (EMF, 2013), several risks emerge by adopting circular economy business models. For instance, the introduction of the production of bio-based materials could directly increase the land or the water use, as other soil contaminants, and may have negative impact on local ecosystem and biodiversity. The resource recovery may lead workers to be exposed to harmful chemicals, as well as toxic materials may be released to the environment. Sharing platform may have environmental rebound effect, for instance, by promoting a wrong behaviour in citizens, i.e. the use of car instead of more environmentally-friendly solutions like bicycle or public transport (Bilitewski, 2012).

Current challenges for companies, instead, are generally related to product design (Favi, Germani, Mandolini, et al., 2016), lack of workers' skills, economic feasibility in the short-term (Rizos et al., 2016), or the actual silos structure of large organizations. Repair, maintain, remanufacturing business models, for instance, mainly depend on the current product design and on their disassembly level. Since many linear manufacturers' business models are based on the amount of sales and on the reduction of production costs, they simply do not take into account the end of life during the production phase

[2]For a detailed lists see also *Circular business models: Developing a sustainable future* (Larsson, 2018) and *Waste to wealth: The circular economy advantage* (Lacy et al., 2016)

and there is no knowledge transfer between the manufacturers and the dismantlers (Favi, Germani, Mandolini, et al., 2016). Common barriers for companies, according to a survey on 30 case studies conducted by Rizos et al. (2016), are lack of support from the supply and demand network, lack of capital, lack of government support or of technical know-how, as well as general information regarding the circular economy. The lack of initial capital (Uvarova et al., 2020) may block companies to invest in circular business model, as well as the delayed and uncertainties on the return of investment of a circular business with respect to a linear model (Linder and Williander, 2017). Moreover, for product-as-a-service business model, a financial risk due to the transfer in ownership from consumer to the producer may occur (Mont et al., 2006). The risk related to the capital tied to the ownership may be overcome thanks to long-term contract (Besch, 2005) but firms' stability may be affected by fashion vulnerability (Mont et al., 2006). Moreover, by adopting circular business models, firms have also to face the risk of cannibalization due to the production of long-lasting products (Linder and Williander, 2017), as the increased dependency to partners due to highly interconnected supply chains may be induce stability risks (Barquet et al., 2016). Finally, according to a report of the *International Reference Centre for the Life Cycle of Products, Processes and Services* (CIRAIG, 2015) and to Nguyen et al. (2014), three other barriers may affect the spread of CBMs:

1. **geographic dispersion**: the complexity of supply chain management in a global market directly affects the implementation of the CE, and not well-developed reverse logistics, or not homogenized national regulations could slow down new CBMs.
2. **complex materials**: the high number of materials in current products, and their complex interconnections (e.g. in electronic and electrical equipment), the lack of tracking of products and materials, as the lack of precise specifications make hard to recover materials and components from products.
3. **the curse of the status quo**: the inertia of human behavior and habits always affects the innovation process. From a business point of view, changing the business model for existing companies could be a challenging and slow process. Barriers from management vision, as well as from technical workers' skills may occur. From the consumer point of view, instead, purchasing a more expensive product of higher quality rather than a cheaper one with a planned obsolescence is not obvious and depends on personal consumers' values.

Despite the barriers listed in the previous paragraph, the adoption of a CBM unleash several opportunities for a company. Rizos et al. (2016) identified a few main enablers for companies to implement new CBMs in their activities: company environmental culture, networking, financially attractiveness, recognition, personal knowledge, and governmental support. Among the others, according to the interviewed companies the most important enabler, i.e. company environmental culture, seems to be related to a previous inclination of companies to environmental sustainability. In terms of resource utilization reduction, the Ellen MacArthur Foundation, for instance, estimated an annual net material cost savings of 23% over the total material consumption for the EU manufacturing sectors. Moreover, the circular economy beyond limiting the use of virgin materials, it may reduce the supply risks and increase the employment (EMF, 2013). For instance, in the Netherlands, new circular businesses should create 54,000 new job places in metal, electronics and electrical equipment industries, as well as in the organic waste management (Bastein et al., 2013). This positive effects may be enabled by the adoption of novel business models looking at the convergence among the circular economy, the sharing economy and/or the collaborative economy (Sposato et al., 2017). Promoting services instead of product sales (i.e. sharing economy), together with collaborative practices (e.g. time banking, purchasing groups, co-working spaces), indeed, boosts closing the loop (or slowing the loop) strategies for firms and businesses, and, at the same time, induces positive effect for society, activating regenerative (social, economic, and environmental) practices as pointed out by the Ellen MacArthur Foundation (2015b). The positive and regenerative impact of adopting circular economy strategies has been further emphatized by the ReSOLVE (Regenerate, Share, Optimise, Loop, Virtualise, Exchange) framework proposed by the EMF as a policy and business tools and widely used to assess and enhance different circular business models (Cagno et al., 2021; Manninen et al., 2018).

5.3.1 Archetypes for product design

With respect to the product design, Bocken, Pauw, et al. (2016) grouped and classified CEBMs into six main archetypes, four related to slowing the loop strategies and two for closing the loop strategies:

1. *access and performance model* to allow users to do not own products;
2. *extension of product value* to exploit the products' residual value before manufacturers take back the products;
3. *classic long model* to offer to customers high quality products with a long lifespan;
4. *sufficiency incentives* to limit users' consumption;
5. *extending resource value* to recycle waste materials and exploit the residual value of resources;
6. *industrial symbiosis* to interconnect industrial processes in order to expoit waste outputs of a process as inputs for another process.

The former four archetypes refer to slowing the loop strategies, while the last two to closing the loop strategies. On top of this classification, Moreno et al. (2016) adapted the archetypes proposed by Bocken, Pauw, et al. explicitly including sharing platform as a circular business model archetype, highlighting the importance such businesses gained in the past years. In their study, they also identified the five most relevant design strategies for the circular economy[3] and they linked each design strategy with an archetype, as shown in Table 5.1, in order to have a conceptual framework to understand the new circular business models.

[3] 1) design for circular supplies (Benyus, 1997), 2) design for resource conservation (Bocken, Pauw, et al., 2016), 3) design for multiple cycles (Conny Bakker et al., 2014), 4) design for long use (C.A. Bakker et al., 2014), and 5) design for system change (Charnley et al., 2011)

Table 5.1: conceptual framework for the circular economy. Adapted from (Moreno et al., 2016).

CBM archetypes	**Design for:**	**Resources**		**Manufacturing**		**Distribution**		**Use**		**Maintaining**		**EoL**	
A) circular supplies	1) circular supplies	A	1	-	-	-	-	-	-	-	-	A	1
B) resource values	2) resource conservation	B	-	B	2	-	-	-	-	-	-	B	2
C) product life extension	3) multiple cycles	-	-	C	3	C	3	C	3	C	3	C	3
D) extending product value	4) long-use	-	-	D	4	D	4	D	4	D	4	-	4
E) sharing platform	5) system change	-	5	-	5	E	5	E	5	E	5	-	5

5.3.2 Waste Hierarchy

Circular Business Models and their impacts on waste production, as well as closing or slowing the loop strategies adopted by firms, have always interpreted according to the waste hierarchy. The waste hierarchy should be considered as the golden rule to minimize environmental impacts and waste production, similarly to the previously discussed rule on the inner circles of the butterfly diagram. Indeed, generally speaking, prevention (i.e. the reduction of in-use materials) is environmentally better than reusing, reusing is better than recycling, and recycling should be preferred with respect to energy recovery, and so on. The European Union introduced a precise waste hierarchy in 2008 with the Directive 2008/98/EC (EC, 2008). The directive defined the priorities to be followed by the country members in terms of waste prevention:

1. prevention, i.e. each intervention measure taken before waste production in order to reduce the amount of waste, the negative generated impacts and the amount of toxic materials;
2. preparing for re-use, the necessary treatment (e.g. checking, cleaning or repairing), to prepare a materials, or a products, already become waste in order to be reused *without any other pre-processing*;
3. recycling, i.e. the reprocess of materials in order to be used again to produce new products regardless the purpose of the new product;
4. recovery, e.g. energy recovery or any other operation to recover materials or components before the final disposal;
5. disposal, any operation aimed at disposing the material into the environment (e.g. landfill, sewage/wastewater.

5.3.3 The 10R model

Circular Business Models (CBM), or more in general circular strategies, may be well-described with the 3R model - *reduce*, *reuse*, *recycle* - (Ghisellini et al., 2016) or with some most recent advancements like the 10R model recently introduced in the Dutch public policies (Platform CB'23, 2019; Potting, Hekkert, et al., 2017). The 3R model simply introduced three hierarchical approaches for the Circular Economy to overcome the linear model. The closed-loop strategy hierarchy is strictly tied to the hierarchy of waste production and of environmental impacts, as introduced by the butterfly diagram in Figure 5.1. Indeed, generally speaking, to *reduce* the production of waste is environmentally better than to *reuse* products or components, which is better than *recycling* materials (EMF, 2013). The most recent 10R model generalizes the common 3R model and focuses on 10 different strategies:

1. *refuse* to produce waste;
2. *reduce* waste production by, for instance, intensifying the use phase;
3. *redesign* products in order to environmentally improve the whole supply chain;
4. *reuse* second-hand products to fulfil the same functions;
5. *repair* products before discarding them;
6. *refurbish*, i.e. modernize old products;
7. *remanufacture* products by using old recovered components;
8. *repurpose* product functions;
9. *recycle* materials to reduce the exploitation of virgin materials;
10. *recover* the energy, e.g. through incineration.

Reike et al. (2018), recently reviewed 69 contributions to circular economy and the R strategies by identifying 38 words commonly used in academic contributions[4]. Although many R-related words appear in the literature, many concepts refer to the same principles and strategies. Moreover, not all authors apply a clearly defined R hierarchy (only about 60% of authors apply it, from the 3R to the 10R hierarchy).

According to Platform CB'23 (2019), figure 5.3 summarizes the 10 different strategies by highlighting their hierarchy. The first 3 strategies - *refuse* (R1), *reduce* (R2), *redesign* (R3) - imply to change existing business models, supply chains and production processes in order to directly reduce and refuse the waste production by redesigning the products or the services and by making them environmentally *"smarter"*. The subsequent 6 approaches - *reuse* (R4), *repair* (R5), *refurbish* (R6), *remanufacture* (R7), *repurpose* (R8) - refer to the closed-loop paths which allow to stop products to become waste and, thus, to avoid the linear End of Life by extending the useful lifespan of them. Finally, the last two strategies - *recycle* (R9), *recover* (R10) - permit to recycle the in-use raw materials for future production processes or, at least, to recover part of the embodied energy. The last approach, i.e. *recover*, cannot be fully defined as a circular approach.

The 10R model relies on the idea of the hierarchical level of waste and on the precise definition and meaning of each R strategy. Despite some concepts seem straightforward, this is not true for all the different strategies; precise definitions are necessary to avoid ambiguities and confusion.

With respect to R4-10 strategies, for instance, Fatimah and Wahidul Karim Biswas (2016) defined repairing as the replacement of old components of a product with new ones, while reconditioning represents the process to restore functionalities and performance of an old or broken product, and, finally, remanufacturing is the process by which a product at its EoL phase is recovered and restored achieving the same performance of the original one with an equivalent new warranty period for consumers. Both processes

[4] re-assembly, recapture, reconditioning, recollect, recover, recreate, rectify, recycle, redesign, redistribute, reduce, re-envision, refit, refurbish, refuse, remarket, remanufacture, renovate, repair, replacement, reprocess, reproduce, repurpose, resale, resell, re-service, restoration, resynthesize, rethink, retrieve, retrofit, retrograde, return, reuse, reutilise, revenue, reverse and revitalize

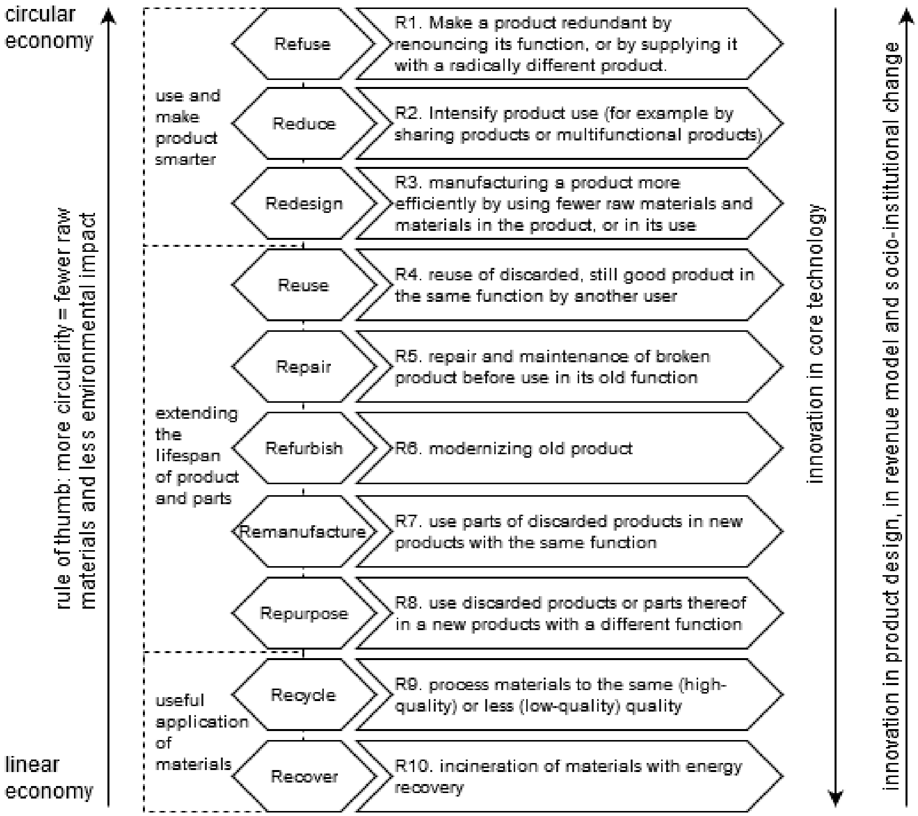


Figure 5.3: 10R model. Adapted from Platform CB'23 (2019)

may imply the substitution of broken and damaged parts. Paterson et al. (2017) defined remanufacturing, reconditioning, and repairing as three similar End of Life (EoL) processes with smooth differences. Reconditioning is a middle-term between remanufacturing and repairing and it implies to restore all broken or damaged components and to give a warranty shorter than new products' warranties. Typically, a reconditioned product results in a lower performance with respect to a new product. Repairing, instead, consists in a selective and punctual operation aimed at adjusting and correcting only single faults and damaged parts. Generally, it needs less work than the other two EoL processes. R4-R8 strategies have many economical, environmental and social advantages. Indeed, for instance, a remaufactured computer is cheaper (Wahidul K Biswas et al., 2013), around 40% of the price of a new one (Fatimah and Wahidul Karim Biswas, 2016), and environmentally better than a new computer. Indeed, remanufacturing, as well as reconditioning or repairing, conserves most of materials and energy (Williams et al., 2003). Moreover, remanufacturing may create job opportunities and consequently may help society in reducing poverty and unemployment (Ferrer, 1997).

Regarding precise definition, *reuse* (R4) implies to use a product for the same function without relevant components adjustment such as for repairing, reconditioning or remanufacturing. The reusing process, according to the BS 8887-2:2009 of the British Standards Institution (2009), is a process *"by which a product or its components are put back into use for the same purpose at EoL"*, while for the EC (2008) it is defined as *"any operation by which products or components that are not waste are used again for the same purpose for which they were conceived"*. In the EU legislation (EC, 2008) a fundamental difference is between reuse and *preparing for reuse*, i.e. the process of *"checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing"*. In other terms, in the case of preparing for reuse, the product had already become waste according to the legislation. Reusing is affordable and possible if a few technical, aesthetic and economic criteria are satisfied (Henriques et al., 2017):

1. components obsolescence (technical and aesthetic) is lower than the product obsolescence;
2. components with high economic and environmental value;
3. during the use phase, component damages are minimized
4. at EoL, efficient collection of the components.

Remanufacturing (R7), instead, regards *"returning a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product"* (British Standards Institution, 2009). According to Ijomah (2002) remanufacturing is the *"only end of life process where used products are brought at least to Original Equipment Manufacturer (OEM) performance specification from the customer's perspective and at the same time, are given warranties that are equal to those of equivalent new products"*. Remanufacturing a product needs (Henriques et al., 2017):

1. components with high economic and environmental value;
2. components can be easily disassembled;
3. at EoL, efficient collection of the components;
4. modularity of product parts.

Recycling (R9), currently the most adopted strategy for EoL, is the process to directly recover the raw materials within a product to produce recycled materials to substitute equivalent virgin materials with the same properties. The BS 8887-2:2009 (British Standards Institution, 2009) defined recycling as *"the processing of waste materials for their original purpose or for other purposes, excluding energy recovery"*. The recycling process consists of several phases where waste are, first, collected, then, processed, and, finally, raw materials are extracted. With respect to the other EoL strategies, such as reuse, reconditioning or remanufacturing, in this case, the product embodied energy is partially lost (Paterson et al., 2017). In order to recycle a material the following criteria should be fulfilled (Henriques et al., 2017):

1. materials can be easily collected;
2. materials should be of high economic and environmental value;
3. product components are made by a few separable materials
4. product components can be efficiently disassembled.

Finally, the energy recovery (R10), i.e. the incineration process, is *"the combustion of waste materials to generate electric or heat power"* (British Standards Institution, 2009) while landfilling is *"the process of disposing of waste by burial"*. In the framework of the Circular Economy, these last two options must be avoided, as they are not closed-loop strategies and because of their huge environmental impacts. Indeed, since the beginning of the XXI century, landfill has been gradually abandoned by the European Union as a possible strategy to manage the EoL of products (EP, 2000; EP, 2003).

To avoid misleading interpretations of the possible EoL strategies among similar and overlapping concepts such as repairing, reconditioning and remanufacturing, Paterson et al. (2017) developed an End of Life decision tool, i.e. a decision tree to understand if a product is recycled, reused, repaired, remanufactured or reconditioned. Through eight questions, the actual EoL strategy can be identified, as depicted in Figure 5.4. Basically, a remanufatured product maintains its embodied energy, has a new warranty equal or better than the original, the main core has been disassembled and all components cleaned, while if the embodied energy is not retained the product is recycled. Intermediate strategies, such as reconditioning, reusing, or repairing does not imply a new warranty (even if they can have a new one). In particular, reconditioning implies that the core of the product (e.g. the motherboard of a laptop) has been disassembled, while reusing and repairing does not. Finally, reusing implies that not all components have been restored adequately as in the case of repairing a product.

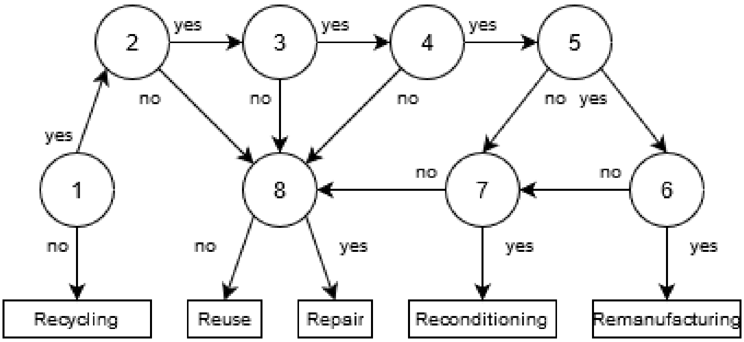
5.4 System thinking and CBM

Up to now, we have seen how novel circular business models cannot be modelled in a straightforward manner. It is necessary to include material feedback loop in order to take into account flows of materials deriving from closing or slowing the loop strategies and, consequently, another way of thinking is needed. Systems thinking emerged in the Fifties as a modelling approach for complex problems (D. H. Meadows, 2008). Originally developed in the computer science field, during the Sixties system thinking was widely used in environmental science, sociology and economics to model the functioning of ecosytems. A system dynamic model studies the causalities (e.g. positive or negative feedback loops) between the single components of a system, thus it analyses the evolution of a system as a whole, avoiding a reductionist approach. In the next subsetion, an example of a novel circular business model, i.e. a take back system for plastic cups, is discussed highlighting the material and money flows and how they change by introducing a new actors in the supply chain.

5.4.1 A case study on reusable plastic cups.

The text of this subsection is partly based on and adapted from the contribution "From flow to stock. New Circular Business Models for integrated systems: a case study on reusable plastic cups" (Dario Cottafava, Riccardo, et al., 2019) presented at the *"23rd International Trade Fair of Material & Energy Recovery and Sustainable Development, ECOMONDO"* held the 5th-8th November 2019 in Rimini, Italy.

The ubiquity of plastic in our everyday life and in any industrial process and com-



1	Is energy retained from original EoL product?
2	Does the product have a core?
3	Is core capable of being disassembled?
4	Has the core been disassembled?
5	Is warranty of product equal to or better than the original?
6	Have all components been cleaned, inspected, repaired to original standard? Had its core reassembled such that the product is in like new condition?
7	Have all major broken components and components on the verge of failure been replaced or repaired?
8	Has the product been restored to an acceptable level in any significant way (and core reassembled if applicable)?

Figure 5.4: EoL decision tree. Adapted from Paterson et al. (2017)

mercial product is unequivocal. Plastic is a very versatile material which has contributed, and is contributing, to many product innovations. Indeed, plastic production is constantly growing since the ‘60s and it reached a global production of 335 Mt in 2016 (Plastics Europe, 2017). However, inefficient and flawed plastic waste management ends in impactful consequence on environment. Plastic leakages, i.e. plastics dispersed into the environment, sooner or later, end up into the oceans. Currently, 150 Mt of plastic is the amount estimated to lie in the oceans (World Economic Forum, 2016) and, every year, more than 8 Mt may arrive to the seas. Littering and plastic leakages into oceans are becoming a global emergency due to the slow degradation and to the so-called microplastics (LI et al., 2016) which enter into the food chain of fishes (Sul et al., 2014), birds (Tanaka et al., 2013) and humans (Wright et al., 2017), causing premature animals deaths. Generally, plastics are fossil-fuel based and energy recovery is a common practice due to the large energy bonded into the chemical structure. Unfortunately, incineration, or landfilling, plastic waste generates a large amount of greenhouse gas (GHG) emissions and, moreover, plastic materials exit from a circular supply chain and cannot be recycled again as a secondary raw materials. Despite the huge effort of practitioners and academic researchers in investigating innovative solutions to increase plastic recycling efficiency, as well as the commitment of policy-makers to adopt new policies and strategies (EC, 2015a; EP, 2019), the Recycling Rate (RR) in European Union (EU) is still far to be considered satisfactory with an average percentage lower than the 50% in EU28 (Plastics Europe, 2017) and a target for Packaging Recycling Rate of 75% by 2030 (EC, 2019b). It is clear that the over-production, and the over-consumption, of plastic products cannot be solved simply by improving the Recycling Rate. Indeed, the single-use plastics constitute the largest part of plastic production, and in 2016 plastic packaging reached nearly the 40% of the global production (Plastics Europe, 2017). New and innovative Business Models have to be introduced in order to face the plastic emergency and to reduce environmental impacts by adopting CBM improving the reuse and the reduction of single-use plastic usage.

Background

Currently, many governments are increasingly dealing with the problem of single-use plastic. For instance, Canada (Walker et al., 2018) and the United States (Wagner, 2017) have promoted initiatives aimed at reducing and gradually eliminating single-use plastics. The connection between the use of plastic (especially the disposable one) and the dispersion of waste in the marine environment has been widely demonstrated; research studies highlighted that, only in the coastal countries, from 4.8 to 12.7 million metric tons of plastic waste end their life into the oceans. These numbers are destined to increase progressively by 2025 (Jambeck et al., 2015). The legislation approved by the European Parliament on 5th June of 2019 (EP, 2019) moves exactly in the same direction, i.e. towards the reduction of single-use plastic components. The EU had already dealt with these topics with the *"European strategy for plastic in the circular economy"* declaring that *"a solution must be found for the growing production of plastic waste and for the dispersion of plastic waste in the environment in which we live, particularly in the marine environment"*. The EU, in order to stem this problem, proposes circular approaches to the use of plastics that give more space to reusable and more sustainable products than those used so far, so as to minimize the amount of plastic waste. For instance, certain products - e.g. plastic straws, single-use plastic cutlery, plastic plates, plastic balloon sticks, cotton bud sticks made of plastic, Oxo-degradable plastics and food containers and expanded polystyrene cups - will no longer been placed on market (EP, 2019). When it will not be possible to stop the use (and the production) of plastic objects, the legislation requires that these be gradually reduced in their use, as well as increasing the proportions of recycled and differentiated plastic waste. Each member State is free to implement the aforementioned regulations in the most congenial manner, providing that the restrictions are *"proportionate and non-discriminatory"*. In Italy, the EU legislation has not yet been implemented but every region is taking steps to issue and implement legislation on its own. The reference law of the Italian legislation does not target directly at plastic waste reduction but tends to eliminate waste at sea, allowing and stimulating fishermen to collect the plastic they find in their nets (Affari Italiani, 2019).

Deposit System background. Currently, dozens of countries worldwide adopted a Deposit-Return System (DRS) with national laws in order to increase the recycling rate of the particular fraction of plastic waste related to the single-use packaging of the food and drink industry (CM Consulting, 2019). Figure 5.5 shows a generic DRS for single-use containers. The supply chain starts from the Producers/Importers (1) who sell the filled beverage containers (e.g. water bottle, plastic bottle for soft drinks, beer cans, ...) to the Retailers who pay the price of the drinks plus a little amount of money for the deposit. Afterwards, Consumers buy beverages, paying the deposit to the Retailers (2) and consume the drinks (3). Thanks to the DRS, consequently, Consumers are allowed to bring back the empty containers directly to the Retailers, or to ad-hoc redemption centers or depots, in order to receive back the deposit (4). At this point, the Retailers, who are aggregating packaging in their private spaces, can give back the gathered empty containers to the Recyclers, receiving back the deposit. In addition, the Retailers may provide data information on the recycling rate, the typology of containers and so on (5). In some cases, as in Iceland, the collection of the empty bottles takes place in some dedicated, automated or manual, return facilities. Finally, the Recyclers process the beverage containers to obtain secondary raw materials which can be sold again to the Producers/Importers (6). Generally, in centralized system, Producers/Importers, in addition to the deposit, have to pay an administrative fee to the Recyclers or to the private/public organization which manage the waste supply chain. Indeed, in many countries the Recyclers represent both the private actors who proper recycle the materials and a public central organization, a national consortium for instance, who manages the entire deposit system.

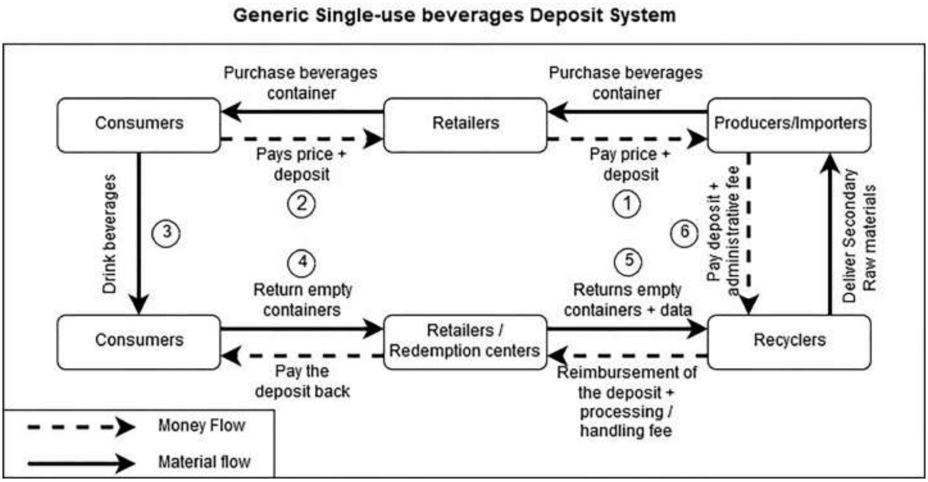


Figure 5.5: Simplified supply chain of a Deposit System for single-use bottles. Adapted from CM Consulting (2019).

The central organization, usually, is responsible for the Clearing System, i.e. it is the entity responsible for the DRS in order to close the money flow. In this framework, the flow is linear up to the Recyclers and there are no financial aid, neither incentive to reduce or reuse products. Indeed, it is straightforward that the material loop is closed only between the Recyclers and the Producers when, effectively, the recovered waste are recycled. As shown in Figure 5.6, the recycling sequence consists of, at least, four steps (Thomas E Graedel, 2011): 1) the Collection, acted by the citizens and the municipalities/local multi-utility companies, 2) the Separation and 3) the Sorting, generally acted by a private-public company, and, finally, 4) the Processing, i.e. the effective waste recycling. The whole sequence can be improved only by increasing the efficiency of each step individually; the final efficiency can be computed as a conditional percentage of the four stages. For instance, as exhibited in Figure 5.6, the final percentage of recycled material (25%) derives from the 50% of the Collection, the 70% of the Separation, the 80% of the Sorting and the 90% of the Processing processes. The last two steps, Sorting and Processing, completely depends on technology and can be improved by technological innovation. The second step, Separation, can be improved by technological innovation as well as on the quality of the collected materials, while the first stage, the Collection, primarily depends on the awareness of the citizens and on proper local and national policies, which stimulate the separate collection, such as door-to-door collection (Teerioja et al., 2012), penalties/taxes/incentives (Miranda et al., 1994) or intrinsic reasons for citizens (Aprile et al., 2019).

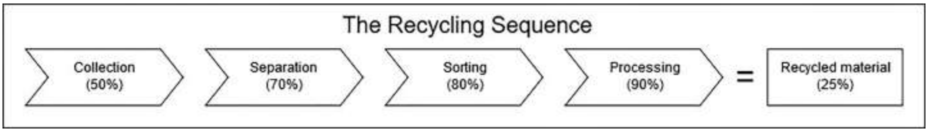


Figure 5.6: Recycling rate for a generic material reverse supply chain. Adapted from Thomas E Graedel (2011).

Although the right policies and incentives may improve the efficiency of the Collection process, its efficiency cannot achieve the 100% due to many reasons such as psychological, administrative or logistics barriers; thus, the entire Recycling Sequence will always be affected by an “original sin”. For these reasons, DRSs have been introduced worldwide in the past decades achieving very satisfactory results in terms of recycled materials even if the physical limit of the 100% of recycled material is still very far. For instance, Croatia achieved a total return rate for single-use containers (Plastic, metal, glass) in 2015 up to 90% with a target of 95%, Denmark of 89% in 2014 with a target of 95%, Estonia reached 82.3% in 2015 and Germany 97% in 2014 (CM Consulting, 2019). On the contrary, the European Union target, according to the Packaging Waste Directive, was 22.5% while the total European Union recycling rate for plastic packaging waste was 40.8% in 2016 (Plastics Europe, 2017). 27.1 Mt of generic plastics was collected over a total production in European Union countries (EU28+NO/CH) of more than 60 Mt of plastics (Plastics Europe, 2017). The percentage of collected waste increased by 10.6%, from 24.5 Mt in 2006 to 27.1 Mt in 2016, and the properly recycled increased by 79% in absolute terms, from 4.7 Mt in 2006 to 8.43 Mt in 2016, while the percentage of recycled waste, over the total collected waste, increased from the 19% in 2006 up to the 31.1% in 2016. Although, the growth both of collected waste and of recycled waste is evident, it is also obvious that the efficiency of the collection and the recycling in EU countries can still be improved, simply by comparing the percentage of plastic packaging properly recycled with the total return rate obtained by DRS. Table 5.2 summarises the Total Return Rate within the countries with a Deposit-Return System regulated by a national legislation versus the plastic packaging RR. Indeed, even if the two data are not directly comparable (one refers to collection rate while the other refers to recycling rate - it is clear that there is a large opportunities of improvement. In fact, a DRS affects the first three stages, Collection, Separation and Sorting, as depicted in Figure 5.6. By multiplying the Total Return Rate with the Processing Rate as indicated in Figure 5.6, a first insight on the improvement margin can be obtained (Table 5.2).

Country	**Total Return Rate (collection + separation + sorting)**	**Plastic Packaging Recycling Rate (hp: processing 90%)**	**Plastic Packaging Recycling Rate (EUROSTAT)**
Germany	97% (2014)	87.3%	48.4% (2016)
Sweden	88,25% (2014)	79.2%	50.7% (2016)
Estonia	82,3% (2015)	74.1%	24.6% (2016)
Denmark	89% (2014)	80.1%	36.1% (2016)
Croatia	90% (2015)	81.0%	41.1% (2016)
Finland	92,6 (2014)	83.3%	25.4% (2016)
Iceland	90% (2013)	81.0%	42.7% (2016)
Lithuania	74% (2016)	66.6%	74.4% (2016)
Netherlands	95% (2014)	85.5%	51.5% (2016)
Norway	96% (2014)	86.4%	44.6% (2016)

Table 5.2: Estimation of Plastic Packaging Recycling Rate. From a Deposit-Return System (CM Consulting, 2019) and Countries Recycling Rate (Plastics Europe, 2017)

Discussion

A case study, i.e. Plastic Free Movida (PFM), in the city of Turin in Italy is described as an example for a Circular BM for a Deposit-Return System for reusable cups. This example shows how by introducing a new actor responsible for the Deposit and the Clearing System in the Material-Money flow (MMF) for single-use beverage containers described in Figure 5.5 it is possible to transform a constant material flow into a temporary material stock. The PFM Business Model has been introduced by the italian NGO greenTO in 2019 in the city of Turin in order to create a distributed and integrated retailers network at urban scale. The BM is based on the adoption of reusable cups by the retailers within an urban area and on a DRS managed by the NGO itself. The definition of “integrated” network refers to the fact that the owner of the reusable cups is a third party stakeholder, in this case the NGO, and the retailers do not have to pay any deposit in advance, as in existing DRS for single-use containers and the introduced cups can be delivered back by consumers to any retail involved in the network. In the following sections, this case study is analyzed in terms of MMF and BM Canvas, highlighting the involved stakeholders and the results from a survey on consumers’ behaviour are presented.

Money Material Flow. In this section, the Money Material Flow is described. Figure 5.7 shows that the DRS analyzed here is pretty similar to the one described in Figure 5.5 related to the common single-use containers DRS; the main difference is a new actor, i.e. the Deposit Manager Organization (DMO), who is the responsible for the Clearing System and acts as a middleman among the Consumers/Retailers and the Producers/Recyclers blocks by managing the Consumer Deposits. First, the container supply chain again starts from the Producers who sell reusable cups to one, or more, Deposit Manager Organization (1) who purchases directly the empty cups without adding any deposit to the price of the cups. The DMO is the owner of the materials and the manager of the deposits. Second, the DMO delivers the reusable empty cups to the Retailers through private agreements receiving back an una-tantum deposit, i.e. a deposit for each requested cup (2) in the first stock. The double direction of the arrows, at this stage, means that retailers can stop and give back, at any time, the furnishment of cups. The agreement between the DMO and the Retailers can be one, or many, year long and it guarantees the Retailers to have a constant stock of cups for all the life of the agreement. Third, as in the single-use DRS, Retailers deliver the cups to Consumers when they buy a beverage by receiving the Consumer Deposit (3) and consequently, Consumers use, and re-use, the cups as many time as they want (4), stacking the cups in a reuse loop. At any time, Consumers can return the empty cups to the retailers by taking back the Consumers Deposit (5). At this point, the DMO takes part again in the supply chain by receiving back, weekly or monthly, the Consumer Deposits and by redistributing empty cups among the network of involved Retailers (6). This step, is necessary to close the reuse loop of the cups. The redistribution, instead, is necessary for an integrated system, i.e. a network of Retailers with the same cup and to guarantee the Consumers to be able to return empty cups to anyone of the involved retailers and not only in the first one where they buy the cups. More precisely, the redistribution balances the number of cups according to the individual agreement between the DMO and the Retailers; in other words, the DMO has to deliver cups to each retail in order to guarantee constantly the same amount of the 1st stock of the step (2). Finally, when the cups reach their end-of-life, in the case of broken, threadbare or unusable cups, the DMO has to collect them in order to send all the materials to the Recyclers in order to enter in the classical and existing Packaging Supply Chain (7,8). This Deposit System stacks the flow of materials within the steps (3), (4), (5) and (6), transforming a constant flow of materials made by single-use products into a, temporary (a few years), stock of materials.

Business Model Canvas. In this section, the business model canvas is presented, in order to document the business model with a visual tool which describes PFM's value proposition, partners, resources, customers, and finances. The PFM's mission is to offer a simple and effective solution to encourage the adoption of consumption models related to reuse practices, starting with drinks consumed in bars, cafes and clubs. The experimentation phase took part in Turin, Italy, in 2019 and during the implementation phase many new activities and players came up, transforming the initial business idea in something more integrated with the city. A couple of considerations on what is described in Figure 5.8:

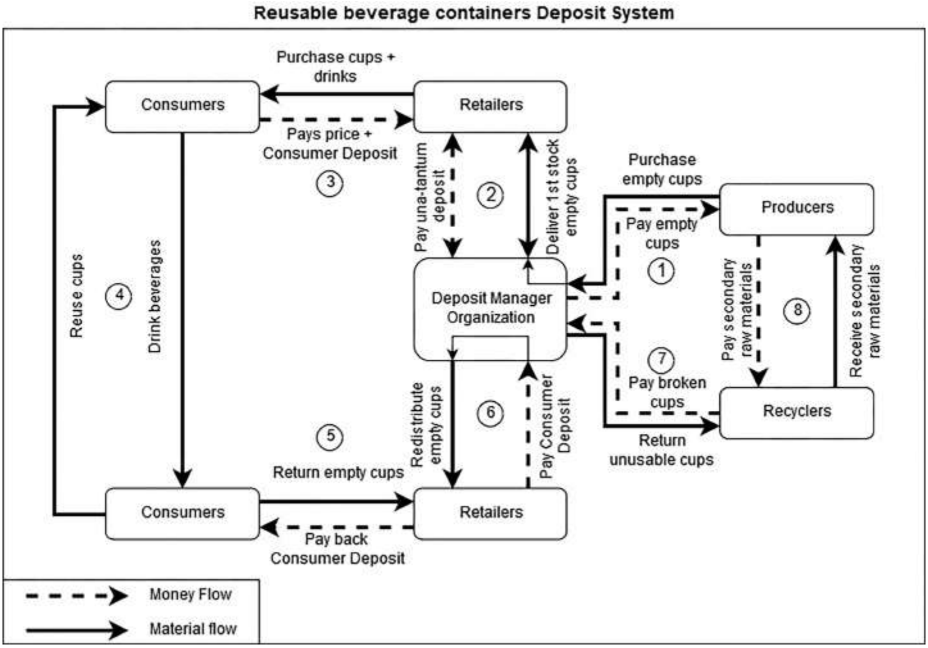


Figure 5.7: Reusable beverage containers Deposit-Return System.

- in order to maximize the awareness on single use plastic consumption and its impact, the partners engagement is crucial; committed partners can involve other new partners and suppliers, enhancing the resiliency of the entire supply chain; moreover, they can involve and engage all the consumers, creating a real community and supporting an indirect education for consumers;
- the integrated system support is the main advantage of PFM. Consumers can turn back or refill their cups in any point of the network (commercial points);
- in order to scale up the business, increasing involvement by new partners is crucial; the business needs to scale also in different operations, as already experimented, such as public events, concerts and exhibitions.

Insights about customers' perception. An online survey has been conducted in the months of June and July 2019 to understand consumers and citizens' drinking habits at night and to explore the perception of users' related to the introduction of reusable cups in the Turin's nightlife. 228 answers were collected (27 in english from foreigners and 201 in italian). The survey was composed by three main sections: 1) personal information (profession, age, gender, ..); 2) drinking habits and nightlife routines; and 3) consumers' feelings and perception about reusable cups and Deposit-Return Systems.

Personal Information. 36.6% of the respondents were male and 63.4% were female, 71% were between 18 and 25 years old, 27.5% were between 25 and 40 and 1.5% between 40 and 60. 77% were students, 20% were employed and the remaining 3%

<table>
<tr><th colspan="5">Plastic Free Movida</th></tr>
<tr>
<td rowspan="2">KEY PARTNERS

- Consumers
- Bars, cafes and clubs
- Bloggers
- Municipalities
- Reuse Business Model Expert
- Engineering partner
- Regulatory Expert
- Other institutionals partners</td>
<td>KEY ACTIVITIES

- Raising awareness of customers and consumers
- Selection, customization and distribution of reusable rigid plastic cups
- Personalized glass washing service, collection and re-delivery
- Redistribution of new cups and deposits
- Integrated management system for the customer relations
- Graphics and communication
- Organization of promotional events</td>
<td rowspan="2">VALUE PROPOSITION

Offer an integrated empty return system for beverages sold, through the use of reusable rigid plastic cups and a customized pay-per-wash service, capable of increase commercial positioning and reduce the waste of single use plastic.</td>
<td>CUSTOMER RELATIONSHIPS

- Direct contact with the customer (email / phone / whatsapp / meeting)
- Newsletter</td>
<td rowspan="2">CUSTOMER SEGMENTS

- Bar owners
- Event organizers
- Catering companies
- Public entities
- Food and Beverage operators
- People sensitive to environmental issues, disposable plastic and social innovation
- People who want to save money on the purchase of disposable products and waste generation
- People who like to share their experiences through social media</td>
</tr>
<tr>
<td>KEY RESOURCES

- Reusable cups
- High performance dishwashers
- Mobility system and transport for the cups redistribution service
- Logistic know-how and integrated systems
- Strong staff commitment on environment protection and social innovation issues
- Communication skills
- Fundraising skills</td>
<td>CHANNELS

- Cups (with customized graphics)
- Web site
- Social Media (Facebook, Instagram)
- Events / concerts / exhibitions</td>
</tr>
<tr>
<td colspan="2">COST STRUCTURE

- Purchase of reusable cups
- Purchase of dishwashers
- Purchase of transport vehicles for cups redistribution
- Marketing & Communication
- HR and salaries
- Taxes</td>
<td colspan="3">REVENUE STREAMS

- Revenues from the refill of the cups capital for each client
- Revenues from the washing and delivery service
- Revenues generated by the licensing of the brand
- Sponsorships and donations</td>
</tr>
</table>

Figure 5.8: BM canvas for a Deposit-Return System for reusable cups.

were unemployed. Finally, the majority were resident in Turin (61%) or lived in Turin as students/workers (28%) while the rest (11%) was living outside Turin.

Drinking Habits and nightlife routines. This section was focused on analyzing the average attendance of users in the nightlife and the average number of drinks per night in order to quantify the possible impact of a Deposit-Return System. Perception on the plastic recycling was also inquired, as well as if consumers usually drink their beverages in plastic or glass cups. There were three questions about the drinking habits: 1) “How many times in a month do you drink in the city at night?”, 2) “How many drinks do you consume on average in an evening?” and 3) “How often are you served the drink you asked for in a plastic cup?”. With respect to the first question, 30% of the participants at the survey drinks more than 4 times per month, 33 between 2 and 4 times per month and 33% declared between once or twice per month. The majority drinks more than one cocktail per night (70% between 1 and 3 cocktails per night and 26% between 3 and 5 and 3% more than 5 cocktails per night). These first questions, together with the first section questions, ensured that the answers came from usual attenders of the nightlife in Turin. Finally, with respect to the third question “How often are you served the drink you asked for in a plastic cup?”, 60% of the sample declared “quite often”, 29% stated "in occasion of big affluence" and only 11% answered "rarely".

Consumers' feelings and perception about reusable cups. In this last section, the aim was to understand the feeling of the consumers about reusable plastic cups and their perception with respect to the service of recycling of single-use plastic cups. There were 6 questions: 1) "When you finish your drink, what do you usually do with the plastic cup?", 2) "What do you think will happen to the plastic cup you've used?", 3) "Would you feel uncomfortable consuming a drink in a reusable cup?", 4) "How much are you willing to pay for a reusable cup if the bartender changes it with a clean one every time you get a new a drink?", 5) "If the bartender gave you the possibility to choose between a reusable and a disposable plastic cup, which one would you pick?" and 6) "If you find a reusable cup on the floor, would you pick it up and bring it back to the bar?". The first two questions aimed at understanding the perception related to the recycling of plastics. Surprisingly, the majority doesn"'t care about throwing out correctly the single-use cups. Indeed, the 48% declared to throw it into a generic bin (not the plastic dedicated bin), 10% declared to leave it in the street, 10% to bring back it to the bar/pub while only the 26% declared to deliver the plastic cup into a plastic bin. This behaviour is further confirmed by the scarce trust in the recycling service. In fact, the second question revealed that 70% believed that plastic cups end into a landfill or directly disperse into the environment (12.7%). Only the 17.3% trusts the recycling service. Finally, the last four questions analyzed the users' feeling about reusable plastic cups. Only 4% declared to feel uncomfortable to drink in a reusable cup due to hygiene, while 48% stated both to be uncomfortable only if the cups are not properly washed and to have no problem with reusable cups usage. With respect to the average price for the deposit, 36% wish to pay less than one euro, 59% between 1 and 2 euros and 5% more than 2 euros. With respect to the fifth question, the majority prefers a reusable cup (93%) against a single-use cup (7%). Finally, the last question analyzed the users' behaviour about picking up empty cups from the street, confirming that the introduction of a Deposit-Return System may solve the littering problem thanks to the deposit. Indeed, 70% declared to collect an abandoned cup, 24% maybe and only the 6% not, I wouldn't.

Concluding remarks

The pilot project described above was run in the city of Turin in the month of july and august 2019 and is still active. It allowed to transform a flow of material into a temporary stock of material. The case study has been validated by a survey on the behavior and the perception of usual nightlife attenders. The results from the survey revealed that night attenders have a scarce trust on the local recycling multi-utility company of the city of Turin. Moreover, answers from the survey pointed out that the majority of nightlife attenders in the city of Turin don't care about correctly disposing single-use plastic cups. The latter feature can be easily solved by introducing a Deposit-Return System for both, single-use and reusable cups, as highlighted from the survey. 70% declared that with a DRS would collect abandoned cups in the street and 24% maybe. Thus, the described Business Model and the related Material Money Flow shows how, introducing a new actor into the classical DRS for single-use cups, it is possible to create an integrated network of retailers at urban level and to boost reuse practice for a targeted product (in this case, plastic cups). Even if the survey's results and preliminary outcome from the pilot project are satisfactory, several aspects have to be further investigated. First, a Life-Cycle Assessment must be performed in order to compare classical single-use container DRS with the proposed DRS for reusable cups and to identify possible inefficiencies, from an environmental point of view, and to reveal the "environmental break-even point". Indeed, the production of reusable cups needs undoubtedly more energy and raw materials (the weight ratio between a single-use and a reusable cup is about 1:10), as well as the repeated washing of the reusable cups requires a large amount of water. Second, current plastic cups producers are selling reusable cups only tested during temporary festivals. Thus, the effective durability of a reusable cup is still to be assessed in the daily life of a bar. It is clear that in bars, restaurant and clubs of a city the usage is much more intensive with respect to a time-limited event. Finally, administrative barriers in different countries have to be analyzed. Existing national, regional or local regulations could stall the scale up of such a model due to hygiene, public safety in the street or to lack of appropriate laws for DRS. On the contrary, a DRS for reusable cups, if implemented at urban scale, could allow to collect information related to social practices, such as social drinking. Merely by developing a smart cup, e.g. a monitoring system which can track drinking habits of citizens and the flow of the cups in the city, it may be possible to collect current unavailable data on several social phenomena related to the nightlife.

5.5 Design a theory

On top of these Circular Economy preliminary concepts, due to the urgency of a new emergent paradigm for our society and due to the blurriness of definitions and approaches regarding the Circular Economy, a collection of legitimate and worthy questions arises: *what characterizes the Circular Economy?*, *What are the main features and set of rules for a Circular Economy?*, *What are the main differences between the Circular Economy and previous concepts?*. Before answering such questions, some broader and more general issues should be addressed due to the blurriness and rough boundaries around the Circular Economy. Many researchers and academics are defining the CE as an emergent paradigm in the management of the society (Geissdoerfer et al., 2017; Reike et al., 2018) but a clear and well-defined theory including previous fields developed in the past decades is still missing.

Circular Economy definition

Currently, in recent years many studies have attempted to define what the Circular Economy is (Dario Cottafava, Ascione, and Allori, 2019; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017). For instance, Ghisellini et al. (2016) extensively reviewed key elements of the Circular Economy by determining the main differences and similarities with previous sustainability concepts and fields, such as cleaner production or industrial ecology (T. Graedel and Allenby, 2010). Despite the increasing interest from the academic community, *"paradigmatic clarity regarding the concept of circular economy has yet to emerge"* (Blomsma et al., 2017). Indeed, in the past years, the circular economy has been defined in several different ways, increasing the blurriness around its definition; for, instance, Bonciu (2014) described CE as *"a new* *frame of mind"*, Blomsma et al. (2017) as *"an umbrella concept"*, or Preston (2012) as *"a paradigm shift"* about how to make and design things. Each definition focuses on a different aspect, embracing and enhancing more design aspects, industrial symbiosis, waste management and reduction, or general environmental impacts due to raw materials exploitation. The Ellen MacArthur Foundation (2017) interpreted the circular economy in a very broad way by defining it as *"an economy that is restorative and regenerative by design"*:

> **Definition 5.5.1 — Circular Economy (1).** A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the "take-make-waste" linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources.

Thus, according to the Ellen MacArthur Foundation, the main aim of a circular economy is to decouple growth from the environmental impacts and the exploitation of raw materials. Geissdoerfer et al. (2017), instead, with their definition focused more on the solutions, highlighting the main strategies and business models to slowing or closing the loops:

> **Definition 5.5.2 — Circular economy (2).** A regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.

According to Reike et al. (2018), there are two main schools of thought about circular economy - the reformist, and the trasformationist ones - which diverge on three main key concepts: 1) resource input reduction, 2) modification of the economy, and 3) inclusion of the three sustainability dimensions. For the transformationist school all these three elements are necessary for the transition towards a circular economy, while for the reformist school they are not. In this sense, the review conducted by Kirchherr et al. (2017), who analyzed 114 different definitions, may support to unfold and juggle the blurriness of CE concept and to better address these three aspects and the differences between the trasformationist and reformist point of view. They coded the 114 different definitions into 17 dimensions, focusing on the 4R framework (reduce, reuse, recycle, and recover), waste hierarchy, systems perspective, enablers (business models, and consumers), sustainable development and the three pillars of sustainability of Elkington (Environmental quality, economic prosperity, and social equity). What they found, in brief, is that generally Circular Economy is strictly tied to the 3R framework (around the 35-40% of the 114 definitions), while a systemic and paradigmatic shift gained less attention. The extension of the Circular Economy to the 4R, or further improvements, is still not very common (only 3-4% of definitions refer to the 4R framework). Furthermore, regarding the sustainability pillars, the economic and environmental aspects are the main targets, while social equity and the impact on future generations appears just in a few definitions. Waste hierarchy, systems perspective and the three sustainability pillars (jointly) are considered by roughly the 30%, 42% and 13% of definitions. In this sense, Kirchherr et al. (2017) argued that this scarce holistic vision among academics may be reflected in a wrong interpretation among practitioners of what circular economy is, or should be, reducing it to simply recycling activities for instance. Finally, only a few academics focused on a multi-level (macro, meso, micro) or a temporal (according to the sustainable development definition) perspective (Fang et al., 2007; Geng et al., 2013; Linder, Sarasini, et al., 2017). Thus, in the current literature the Circular Economy is mainly intended as an applied research field to improve the sustainability of products or processes, and the paradigmatic point of view is almost completely missing from the academic debate, highlighting the necessity to questioning deeper what the circular economy, or a circular *thing*, is. As many researchers and practitioners agree that the new circular economy paradigm strongly relies on the re-design of products' supply chains (Schenkel et al., 2015), engaging all relevant stakeholders, and on the introduction of new business models (Bocken, Pauw, et al., 2016), the transition of the third industrial revolution, as described by Rifkin (2015), may be wisely driven and supported towards a circular economy thanks to the *Information Systems* (Britannica, 2020). A brief introduction to Information Systems will be provided in the next paragraph.

Information Systems

To face up such a complex challenge, *Information Systems* may support to sculpt the existing blurs. An Information System (IS) is generally defined as a system aimed at collecting, processing, storing, and distributing information (Piccoli et al., 2019). The Encyclopedia Britannica (Britannica, 2020) defines a IS according to the following broad definition.

> **Definition 5.5.3 — Information System.** An integrated set of components for collecting, storing, and processing data and for providing information, knowledge, and (digital) products.

In general, an Information System is a set of components aimed at producing information (Kroenke et al., 2010). According to Kroenke et al. (2010), the five essential components are:

1. *hardware*, the necessary machineries (e.g. a computer),
2. *software*, the program used to process the information,
3. *data*, the underlying information to be processed,
4. *procedures*, the methods adopted to analyze the data
5. *people*, the final users or the involved stakeholders.

According to these definitions, an Information System explores and investigates not only technological or social systems. Basically, IS focuses on the *"phenomena that emerge when the two interact"* (Gregor et al., 2007). Indeed, for the Association for Computing Machinery (ACM), IS practitioners focuses on *"integrating information technology solutions and business processes to meet the information needs of businesses"* (Shackelford et al., 2005). Depending on the aim or the structure, there exist many different ISs such as *decision support systems* (DSS), aimed at supporting decision-making processes (Keen, 1980), or *knowledge management systems* (KM), which main goal is to provide and manage the knowledge related to an organization (Girard et al., 2015), just to name a few.

5.5.1 Information System Design Theory

Information System Design Theories (ISDT) focus on how to conceive and design an Information System (Gregor et al., 2007) and they are of fundamental importance. ISDT, according to Liang et al. (2004), represents the necessary foundation to design specific architecture as, for instance, decision support or knowledge management systems. Gregor et al. (2007) declared *"understanding the nature of ISDT supports the cumulative building knowledge, rather than the re-invention of design artifacts & methods under new labels in the waves of fads and fancies"*. Walls et al. (1992) described ISDT as *"a prescriptive theory which integrates normative and descriptive theories"*. Descriptive and predictive theories aim to describe a phenomenon, i.e. *what is it*, or to predict future behaviours, i.e. *what will it be*; thus, they differ from normative and prescriptive theories which aim to define how an artefact, a norm, or a process *should be*. Roughly speaking, descriptive and predictive theories refer to science, while normative and prescriptive theories refer to philosophy and design. In this sense, Walls et al. (1992) proposed a few statements to characterize design theories. In their opinion, design theories must consider goals as intrinsic rather than as extrinsic as in explanatory and predictive theories. Second, design theories are prescriptive and composite theories. Prescriptive because they tell *how to* and *what should be* (fundamental aspect of normative theories) rather than *what is* (aspect of descriptive theories) or *what will be* (predictive theories). Composite because they integrate descriptive, predictive, or normative theories and put them into practice. In other words, a prescriptive law should be expressed as *"if you want to achieve Y, then make X happen"* instead of *"X causes Y"*. Thus, ISDT could be the right lens to face up the Circular Economy challenge and paradigm shift because design theory prescribe the fundamental properties an artifact *should have* to achieve a certain goal.

To understand the approaches and methodologies to design theory for IS, a historical view on the philosophy of science should help. Generally speaking, the philosophy of science defines a theory as an entity which provides explanations or predictions, and is testable. According to K. R. Popper (2002), theories belong to the so-called *World 3*. *World 1* represents the material things, the objective world, in the *World 2* lie the mental states, i.e. the subjective world, while a theory objectively exists within the abstract *World 3* made by human. Indeed, K. Popper (2002, p.37) stated that *scientific theory are universal statements*. Similarly, Habermas (1984) defined the objective and the subjective worlds of real states and personal beliefs, respectively, and the social worlds regulated by social norms and relationships. More precisely, Robert Dubin in his book *"Building Theory"* identified the essential components to build a scientific theory (Lynham, 2002): 1) units, 2) laws of interaction, 3) boundaries, 4) system states, 5) propositions, 6) empirical indicators, 7) hypotheses, and 8) testing. The first four components compose the *theory development* of the theory-research cycle resulting in a conceptual framework for a theory. *Units* follow the *laws of interaction* within declared *boundaries* and they represent the focus of the theory. The *system states* are the system conditions under which the units may behave differently. The last four points, instead, belong to the *research operation*, aimed at empirically verifying and testing the theory. The *propositions* represent the truth statements to be validated through *empirical* *indicators*, and testable hypotheses (i.e. *hypotheses* and *testing*). The Dubin's theory-research cycle is a deductive approach to create knowledge (Lynham, 2002) according to the idea that a theory is a *general statement from which particular inferences may be deduced* (Honderich, 1995, p.386). In other words, deductive reasoning, also defined as top-down approach, is the logical process to explain a precise phenomenon starting from a general theory, while inductive reasoning is the opposite process, i.e. starting from case studies a general theory is described. The emergence of a new theory, or of a new (technological) *artifact*, according to Heidegger (1977, p. 6-12), must fit the four Aristotle's causes - causa finalis, formalis, materialis and efficiens - which define a *poiesis*, i.e. the arising of something from out of itself. The four causes respectively refer to four fundamental questions about an artifact - what thing is for, what it means to be the thing, what it is made from, what made the thing. Although Dubin's thought and his theory-research cycle has been largely adopted as theoretical framework together with the idea of K. Popper (2002) that scientific theories are universal, other schools of thought, more focused on technologies, adopted the constructivism paradigm. Constructivism in mathematics, for instance, assumes that in order to prove the existence of a mathematical object, first, it needs to be built up (Bridges et al., 2018). In constructivist design theory, for instance in ISDT, as stated by Gregor et al. (2007), *"the construction of an artifact that is sufficiently novel is seen as a significant contribution in its own right"*.

Table 5.3: Essential components for design theories. Comparison of three approaches. Source: Gregor et al. (2007)

Gregor (2007)	**Dubin (1978)**	**Walls (1992)**
1. Purpose and scope	Boundaries	Meta-requirements
2. Constructs	Units	
3. Principles of form and functions	Laws of interaction	Meta-description
4. Artifact mutability	System states	
5. Testable propositions	Propositions	Product hypotheses Process hypotheses
6. Justificatory knowledge		Product kernel theories Process kernel theories
7. Principles of implementation		Design method
8. Expository instantiation	Hypotheses and empirical indicators	

Information System Design Theory was firstly introduced by Walls et al. (1992), starting from Dubin's theory-research circle (Lynham, 2002). They identified seven components for ISDT: 1) meta-requirements, 2) meta-description, 3) design method, 4) kernel design product theories, 5) testable design product hypotheses, 6) kernel design process theories, and 7) testable design process hypotheses. With regards the seven proposed aspects, the *meta-requirements* are the set of goals the design theory should address, while the *meta-description* component refers to the group of artifacts that needs to address the meta-requirements. Walls et al. (1992) used the word *meta* to emphasize that design theories refer to classes and groups of goals and artifacts and not to a single one. Finally, the *kernel theories* represent the theoretical background from natural or social sciences to be taken into account in order to test the hypotheses. The *product* and *process hypotheses* are necessary to evaluate if the *design method* is consistent with the *meta-description* and *meta-requirements*. Similarly to Dubin's *"Building Theory"*, the first components are necessary to define the conceptual framework, while the latter ones to test and validate it. In particular, they gave no importance to the *units* while they focused more on the explanation of a theory (kernel design product/process theories); indeed, these two requirements aim at identifying a robust explanation for the artifact. Finally, Gregor et al. (2007), starting from the work of Walls et al. (1992) developed in the early nineties, improved older definitions of ISDT by identifying eight fundamental components for ISDT:

1. *purpose and scope*, i.e. the causa finalis, the goals, scope and boundaries of the theory or of the artifact;
2. *constructs*, i.e. the causa materialis, the entities object of the theory;
3. *principles of form and function*, i.e. the causa formalis, the architecture of the IS artifact;
4. *artifact mutability*, the eventual modification of the artifact;
5. *testable propositions*, the statements to be tested for the theory.
6. *justificatory knowledge*, i.e. the kernel theories, underlying natural, social or economic laws and theories;
7. *principles of implementation*, i.e. the causa efficiens, the necessary processes to apply the theory;
8. *an expository instantiation*, the real implementation for validation.

Table 5.3 summarizes and compares the main components of Dubin's research framework with the ones proposed by Walls et al. (1992) and Gregor et al. (2007).

5.5.2 Open research questions

If i had an hour to solve a problem and
my life depended on the solution,
I would spend the first 55 minutes
determining the proper question to ask,
for once I know the proper question,
I could solve the problem in less than
five minutes.

Albert Einstein (Wahl, 2016)

"Our culture is obsessed with quick-fix solutions and immediate answers. Time is at a premium and we don't want to waste it dwelling on questions", Wahl stated at the very beginning of his book *Designing Regenerative Cultures*. *"Questions, more than answers, are the pathway to collective wisdom"* Wahl continued. According to his thought, a change in mentality from answering to questioning, from stating to listening,

and from controlling to feeling is necessary for *"our species to not just survive, but to thrive"* within the planetary boundaries; *"to move from a zero-sum culture (win-lose) to a non-zero sum culture (win-win)"*, it should be also ensured the win of the nature (win-win-win). Within the regenerative cultures paradigm the three wins depict the individual (i.e. well-being), the collective (society), and the planetary (Nature) levels (Wahl, 2016, p. 20-21). Thus, on top of these considerations, the very first step, to explore a new emerging paradigm such as the circular economy, should be to focus on the relevant and right questions. For instance, some starting questions to focus on could be:

1. what are the relationships between design criteria and waste hierarchy (e.g. the 10R framework)?
2. how do they influence the waste production?
3. how do these relations affect a multi life-cycle assessment?
4. can the impact be predicted for an infinite loop of a product/material?
5. how can recursive recovering of materials, products or components be modeled?

Some of these questions are partially addressed by some current indicators or methodologies, others are not. To evaluate, monitor, and even facilitate a transition towards circularity well-designed tools, indicators or methodologies are required. As emerged from the previous chapters, measuring the circularity involves different levels - macro (international, national, or regional), meso (eco-industrial parks, supply chains), and micro (single company, or product) - different aspects - environment, economy, and equity - different processes (e.g. 10R framework), and life cycle phases (e.g. extraction, production, use, EoL). Regarding the different levels, according to Kristensen et al. (2020) for instance, a detailed knowledge about how to measure the circularity is still missing, in particular, in their opinion, at the micro level. Starting from the question, *which micro level indicators exist for CE, and how do they align with the three dimensions of sustainability?*, they reviewed 30 indicators and classified them into 8 main categories depending on the focus according to: 1) recycling, 2) remanufacturing, 3) reuse, 4) resource-efficiency, 5) lifetime extension, 6) waste management, 7) end-of-life management, and 8) multidimensional indicators. They concluded that currently there is no common recognized standard to measure circularity and only a few focus on micro design aspects such as design for disassembly or lifetime extension. Moreover, the majority of circular indicators measures the outer circles (i.e. recycling, waste management) while only a few indicators examine the inner ones (e.g. repairing, reuse). From this review, as it will be discussed more in detail in chapter 7 about How to assess circularity, what emerges is a lack of a common ground. Indeed, several indicators or methodologies focus on the waste and end-of-life management or on resource-efficiency without analysing micro design for disassembly features (Di Maio et al., 2017), for instance, while others focus on computing the time for disassembly, to be intended as the main driver for the recovering cost, but lack of a precise environmental impact assessment (Vanegas et al., 2018). Moreover, no indicator has a systemic perspective, linking results and findings at micro level with the planetary boundaries. Thus, in my opinion, from this first part of the thesis a first conclusion can be drawn. A precise and strict definition, of what a circular *thing* is, is necessary. A first research question should be stated, in its most general way, as:

Question 5.1 How a *circular thing* is defined? What are the main features to define a circular object?

Consequently, to define an object, according to the four causes of Aristotle, one can further questioning:

- *Material Cause*: What is it made of?
- *Formal Cause*: How is it arranged?
- *Efficient Cause*: What/who made it?
- *Final Cause*: What it is its purpose?

Every object should be designed taking into account the four causes. Just to give an example, a table is made of wood, or of other materials (Material cause), its shape defines the formal cause, the producer (e.g. a carpenter or a designer) and the adopted method/process are the efficient cause, while its final cause, for instance, is allowing people to eat, work, and/or study on it. In brief:

Question 5.2 What are the four causes of a *circular thing*? In other words, how can a *circular thing* be described in terms of the composition (the what), the shape and form (the how), the process (the who), and the purpose (the why)?

Once the four causes are stated and described, the essence of a *circular thing* should be clear; only at this point, following the fundamental questions about circularity and its essence, a general circular economy theory may be discussed moving one step further, starting from the eight requirements of an IS artifact (Gregor et al., 2007). In this framework, the purpose and scope (the why/the causa finalis), according to Table 5.3, refer to the boundaries of the artifact. Following the discussion of the previous chapters, the boundaries of a *circular thing* should refer to the planetary boundaries, and not only to the object itself, as its purpose should be to lie within the Earth forever and to allow humankind to live in the *safe and just space* (Raworth, 2017). Thus, referring to the construct (i.e. the basic unit/the causa materialis), principles of form and function (the causa formalis), artifact mutability (i.e. the system state), testable propositions and justificatory knowledge, how can they be defined to allow a *circular thing* to lie forever within the planetary boundaries? In other words,

Question 5.3 What are the characteristics of the six requirements (purpose and scope, constructs, principles of form and function, artifact mutability, testable propositions, and justificatory knowledge), necessary to define theoretically an IS artifact according to the Information System Design Theory, which define a Circular Economy theory?

Finally, once the fundamental requirements of a Circular Economy theory are stated and, as consequence, of a *circular thing*, an IS artifact need to be instantiated and tested. At this point, the *principles of implementation* (the causa efficiens), and an *expository instantiation* are necessary to evaluate the validity of the theory and to test the hypothesis under the defined boundaries, and interactions laws. In order to instantiate the artifact, it is necessary, first, to explore existing tools, methodologies, or approaches, and, second, to identify the proper one (perhaps, ones?). The existing theories and tools will be described in next chapters (6 and 7). In this sense, a final set of questions could be stated as: *which are the most proper tools and methodologies to assess the circularity of things?*, *How to connect the micro-aspects, e.g. the design criteria, of things to planetary boundaries?* and so on. More concisely:

Question 5.4 What are the general principles of implementation, i.e. the fundamental modules/blocks, needed to evaluate, monitor a *circular thing*, and, eventually, to forecast and predict its behaviour in time?

In other terms, recalling the definition of *Circular Commons* given in chapter 4, further relevant questions in order to implement a Circular Economy theory should be:

Question 5.5 What are the the fundamental modules/blocks to manage a *Circular Commons* in a *indefinetely-lasting* dynamic equilibrium within the planetary boundaries?

Concluding, in order to validate the theory and the hypothesis an expository instantiation is necessary. Only at this point a general theory, a new paradigm may emerge. To do so, first, the underlying theories and schools of thought of Circular Economy (chapter 6) are presented and discussed, and as far as I know, the necessary theories and methods for a Circular Economy theory are summarized. Then, in chapter 7 the known and most common methodologies, tools, and approaches used to evaluate the circularity are briefly discussed, attempting to focus on the *big picture* of Circular Economy. In part III, three examples and applications of current methodologies are presented (chapter 8), while in chapter 9 a definition of a *Circular Thing* is given, and an IS artifact, in its most general version according to the ISDT, is discussed to introduce a few general propositions a *circular thing* should fulfill to be considered a circular object within a Circular Economy theory.

6. The Circular Economy

Break me. Break me into beauty.
For my father once said, "Through the
hottest fire comes the purest gold."
So break me.
For I burn and I melt into cracks made
by careless hands that once held me
closely. Toss me to the flames and
break me.
Break me into beauty.

Lauren M. Garcia

Kintsugi is the japanese art to transform scars into learnings. It's an old japanese art specialized in repairing jars, pots and urns with powder of gold in order to show, in a clear way, the fixing. The Kintsugi aim is not only to repair something broken but to renew it by giving it a new value and converting a problem into an oppportunity. In this way the repaired pottery becomes a symbol of beauty and strength (Keulemans, 2016).

Kintsugi art well-depicts and represents, as a metaphor, the new Circular Economy (CE) paradigm, especially in its Regenerative Design meaning where a broken product has not to be considered waste but a new resource able to create new value - even more than the original one - in a regenerative way, as recently introduced by the term *upcycling* (upgrading + recycling) to refer to recovered products which improve their value after being recycled/reused (Wegener, 2016). In this sense, the CE is only the last conceptualization attempting to create a theoretical framework to link sustainable development with the planetary boundaries in order to face the ongoing ecological crisis. It emerged as a new framework in the last decades, following the historical critiques of the current economic system, where economic profits have been always considered of primary importance with respect to environmental/social profit (A. Schneider, 2015), and where they have been even regarded more worth than ethical and moral principles (Besio et al., 2014).

In this chapter a brief overview on the history and the previous schools of thought is provided in sections 6.1 and 6.2, while in section 6.3 - *Circular Economy: relabeling or new paradigm?* - the findings of a review of concepts related to CE, conducted on the Scopus database and Wikipedia, is discussed, pointing out the most relevant existing concepts and their relationships with the circular economy. In the last section, a more clear picture is framed of what CE is, represents, and includes.

6.1 History and background

The origin of the term Circular Economy traces back to the late Eighties/earlier Nineties (Pearce et al., 1990), although explicit mentions of circular flows may be found in the early debate related to environmental economics in the Sixties/Seventies (Boulding, 1966) or even earlier, from the XIX century (Cucciniello et al., 2018; Lancaster, 2002). Thus, the CE concepts are rather than new. For further detail about the origin of the term Circular Economy, see the focus 6.1.

Focus 6.1 — Origin of the term Circular Economy. The term Circular Economy is generally attributed to Pearce et al. (1990) who in their book *Economics of natural resources and the environment* entitled the introductory chapter *The Circular Economy* defining the connections between the environment and economic activities through the Input-Output tables (Andersen, 2007). However, it is well known that one of the historical mentions related to avoid waste and to transform it into profitable products traces back to 1848. The first President of The Royal College of Chemistry R. W. Hofmann, indeed, stated *"in an ideal chemical factory there is, strictly speaking, no waste but only products. The better a real factory makes use of its waste, the closer it gets to its ideal, the bigger is the profit"* (Lancaster, 2002, p.26).

Other studies, instead, traced back the CE origin to the XIX century with the work of Peter Lund Simmonds (1814–97), writer on technological subjects during the Victorian period in Great Britain (Cooper, 2011). Simmonds, born in Aarhus (Denmark), was adopted by Lieutenant George Simmonds (Greysmith, 2020), of a british naval family, and worked for several years in the company of his family, a fundamental experience for his later books. Indeed, his writings focused on the colonial management and, in particular on waste products, utilization and management. In 1844, he founded a journal, *Simmond's Colonial Magazine and Foreign Miscellany*, dealing with topics such as colonial government, and the improvement of natural resources exploitation. In 1862, he wrote the book *Waste products and undeveloped* *substances: Or, hints for enterprise in neglected fields* where he discussed the waste management as an opportunity for the industrial production. Although not interested in pollution or environment-related issues generated by waste production, Simmonds may be considered one of the precursors of the recent Industrial Ecology and Circular Economy because of his studies on waste and materials recovering (Cooper, 2011).

However, the most recent debate about circularity emerged in the Sixties with the birth of the modern environmental economics. The idea of the "The economics of the coming Spaceship Earth", and the necessity to study the ecological cycles, dates back to 1966 (Boulding, 1966), while the idea of a closed-loop economy (1976) refers to a report written in 1976 to the Commission of the European Communities by Geneviéve Reday-Mulveyan and Walter R. Stahel (Walter R Stahel, 2020). Although the official definition is still to be precisely attributed to an author, it is undoubted that the Circular Economy, even if in its prototypal version, gained attention with the rise of the Life Cycle Thinking in the Eighties/Nineties.

■

It is only in the first half of the 20th century, when global industrial production speeded up as a consequence of the two World Wars and of the second industrial revolution (Rifkin, 2015), that the academic debate started to focus on the uncontrolled generation of waste and pollution issue (Reike et al., 2018), and policy- and decision-makers and the public opinion rose their awareness about the human-nature relationship (Carson, 1962). In this respect, the awareness and the urgency about world resource depletion emerged as a global challenge to be faced thanks to the *The Limits to growth* report published by D. H. Meadows, D. Meadows, et al. (1972), and in the seventies, after this incubation period, the circular economy archetypes started to be popular. Reike et al. (2018) identified three main historical phases from the seventies onwards:

1. **1970-1990: CE 1.0**. In this period, the 3R - reduce, reuse and recycle - concept emerged as a general framework to wisely manage waste production (Kirchherr et al., 2017). Governments, especially in US and Europe, focused on "end-of-pipe" solutions, waste reduction policies, and "polluter pays" regulations rather than on the prevention and on the safe-guard of the environment (Gertsakis et al., 2003). Several authors argued that it is in the period from 1970 that the precursors of the circular economy such as the industrial ecology (T. Graedel and Allenby, 2010) and the life cycle thinking was born. Since then, recycling and separate collection, indeed, constantly increased their efficiency;
2. **1990-2010: CE 2.0**. These decades were dominated by the sustainable development concept of Brundtland et al. (1987) and by the idea of a balance between human activities and the environment. Life cycle assessment moved from the academic debate to practitioners and firms as a tool to certify and promote enterprises will towards a sustainable development and environmental protection (Blomsma et al., 2017). Other approaches and methodologies were developed, such as the Design for Environment (DfE), and adopted by practitioners and businesses (Yarwood et al., 1998), meanwhile an increasing sense of urgency spread worldwide thanks to the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2020) and the conference of the Parties (COP) held annually (UNFCCC, 2020). It is

in the first decade of the XXI century that the CE appears in scientific literature (Reike et al., 2018);

3. **2010-2020: CE 3.0**. The adoption of the 17 SDGs (UN, 2020) and the Agenda 2030 (UN, 2015b) by the United Nations, as well as the increasing loss of biodiversity, and the climate change emergency, marked the last decade.Thanks to the efforts of the Ellen Mac Arthur Foundation, among other institutions, the CE gained momentum as one of the solutions to face up the shortage of raw materials and of environmental pollution while maintaining the economic growth, and, thus, safeguarding job employment.

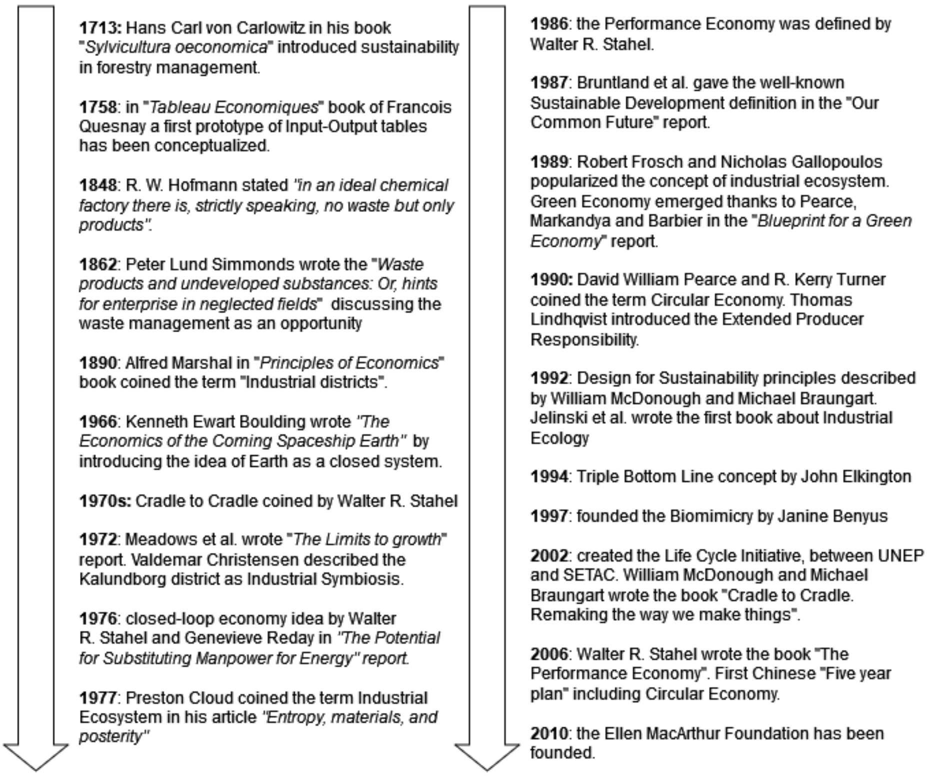


Figure 6.1: Timeline of the concepts related to Circular Economy. Adapted from CIRAIG (2015).

Figure 6.1 summarizes the fundamental historical steps in developing the main concepts related to CE in the past two centuries. Although the origin of CE-related concepts are quite old, the majority of achievements date back to the last two decades. In the period 1990-2010, public policies focused on increasing the recycling rate, from household to industrial waste (Sakai et al., 2011). Primarily business and policy oriented, the CE has been already implemented in the Chinese *"Five Year Plans"* (since the

11th one, i.e. since 2006) (Zhijun et al., 2007). In United States, instead, municipal Solid Waste (MSW) recycling rate in United States rose up to a 33%, from an initial 16%. At the same time landfilling decreased to 55% from the initial 70% of the total (Kollikkathara et al., 2009). In Japan, according to Sakai et al. (2011), MSW recycling rate increased from 20% in 2006 up to the 24% target in 2015, with very high rate for specific materials, e.g. 62% paper, 91% glass. Although European policies attempted to homogenize targets (see focus 6.2), the evolution of each country within the EU followed different paths. Northern countries moved faster than southern countries. The Netherlands, according to Milios (2013) for instance, in 2010 reached a MSW recycling rate around 50% and landfilling was almost 0%. As one of the global precursor, The Netherlands recycled almost all (98%) construction waste already in 2010, even though downgraded (Bergsma et al., 2014). A similar increase in recycling rates can be seen in almost all EU countries.

Focus 6.2 — EU Circular Economy Action Plan. In the last decades the European Commission (EC) sped up the transition towards the Circular Economy, and towards a carbon neutral European Union, by proposing and adopting dozens of new policies to reduce and prevent waste production, to increase recycling practices and recycled content in products, as well as to promote innovative sustainable and regenerative practices. The principal strategies of the European Commission has been summarized in the *Closing the loop - An EU action plan for the Circular Economy* of 2015 (EC, 2015b) and in the most recent *A new Circular Economy Action Plan For a cleaner and more competitive Europe* (EC, 2020b). Both action plans targeted the main challenges related to the prevention and reduction of used materials, and corresponding environmental impacts, by converging and merging several previous directives. For instance, starting from the Ecodesign directive (EC, 2009) that was mainly focused on energy-related products, with the new CE action plan the EC will target both the energy consumption of products and the waste prevention by setting clear target for reparability, recyclability, upgradability, and durability. In this direction, the *right to repair* has been recently approved, forcing producers to release the scheme and layout of certain products in order to facilitate the repairability. At the same time, setting a clear waste hierarchy (EC, 2008), the EC is promoting circular practices by preventing the most impactful practices (e.g. landfill, energy recovery). On the other hand, by adopting minimum target for recycled content, or by banning of toxic materials, the EC is also preventing the use of raw and toxic materials improving the environmental impacts to produce certain products (e.g. plastics). In 2015, several priority areas have been declared [a] in order to face with the most urgent environmental (e.g. plastics in the ocean), geopolitical (e.g. critical raw materials), or to improve the most impactful sector (e.g. construction and demolition). Some of the treated aspects are discussed in theoretical terms or with concrete examples and applications within this work.

If the first action plan was pragmatic and applied without emphasizing a holistic and systemic vision, the new Circular Economy Action Plan (released in 2020) merges precise policies and targets for firms with clear methodologies and pilot approaches and with a more holistic and systemic vision of a carbon-neutral, and resilient European Union.

> *Scaling up the circular economy from front-runners to the mainstream economic players will make a decisive contribution to achieving climate neutrality by 2050 and decoupling economic growth from resource use*

This introductory sentence, together with

> *the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries*

opens the *A new Circular Economy Action Plan For a cleaner and more competitive Europe* showing a strong vision for the next decades. Avoiding to report every single proposed actions, it is noteworthy how the European Commission is leading the transition also by implementing and realeasing public tools and methodologies to assess the circularity of products (see for instance the novel Product Environmental Footprint apporach). ■

[a] Priority area in the Circular Economy Action Plan: plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based products

6.2 Schools of thought

According to the Ellen MacArthur Foundation (2020), the main schools of thought over which the CE is based are the cradle to cradle (Braungart et al., 2007), the performance economy (Walter R. Stahel, 2010), biomimicry (Benyus, 1997), industrial economy (T. Graedel and Allenby, 2010), regenerative design (Lyle, 1996), and the blue economy (G. A. Pauli, 2010).

6.2.1 Cradle to Cradle

When faced with blankness,
nature rises to fill in the space.
This is nature's design framework:
a flowering of diversity,
a flowering of abundance.

(McDonough et al., 2010, p.118)

The term Cradle to Cradle (C2C), attributed to Walter R. Stahel in the 1970s (C2C, 2021), has been popularized only at the beginning of the new millennium thanks to the book *Cradle to cradle: Remaking the way we make things* written by McDonough et al. (2010). The idea of the C2C assessment derives directly from the Life Cycle Assessment but, according to its authors, it is deeply different as LCA is strongly linear in its approach and it lies on the "do less bad" eco-efficient philosophy, *"a failure of* *imagination"* (McDonough et al., 2010, p.67), rather than a more regenerative eco-effectivenness point of view (see section 5.1) (CIRAIG, 2015). Using their words, indeed, *"eco-efficiency is a reactionary approach that does not address the need for fundamental redesign of industrial material flows"* while eco-effectiveness is based on *"the successful interdependence and regenerative productivity of natural systems"* and it *"eliminates the need to associate guilt with human activity"*, by interrelating man and nature as mutually beneficial (Braungart et al., 2007). Eco-effectiveness intends to regenerate natural and artificial ecosystems, or, in other words, to improve them - e.g. through upcycling of products rather than recycling (CIRAIG, 2015). The C2C philosophy is grounded on and inspired by the nature's metabolism where all waste of a natural process are nutrients for other processes, entering in an infinite cycle. The CE, in particular, inherited from C2C many fundamental concepts and precise terms. In the C2C philosophy, nature's cycles (biological metabolism) are to be taken as a model for industrial products and materials (technical metabolism) (EMF, 2017). Indeed, Cradle to Cradle main principles are: *"waste equals food"* - valid for both biological and technical metabolisms - and *respect diversity* - i.e. imitate nature's design framework based on abundance rather than *one-size-fits-all solution* (McDonough et al., 2010, p.126-127).

More precisely, McDonough et al. (2010, p.165-186) suggested five principles for eco-effectiveness solutions:

1. *"free of"* known harmful substances is the first step toward an eco-effective design, i.e. a *conditio sine qua non*;
2. *"personal preferences"*, when no precise information are available, based on the best possible choice made on the partial available information;
3. *"passive positive list"* should be consulted in order to design with an eco-effective approach. The C2C standard provides: 1) an *X list* of harmful substances (carcinogenic, mutagenic, such as asbestos, benzene) to be avoided, according to the International Agency for Research on Cancer (IARC), 2) a *gray list*, i.e. toxic substances without any known available alternative, and 3) a *P list* of positive substances, which may even regenerate health and wellbeing.
4. *activate the P list*, by selecting materials which may flow into the biological cycle, or products and components which can be upcycled.
5. *Reinvent* products/processes integrated within the ecosystem to create positive impacts.

Following these five steps, McDonough and Braungart recently founded the *Cradle to Cradle Products Innovation Institute* and released a *Cradle to Cradle Certified Product Standard* based on five pillars including the three pillars of sustainability (C2C, 2016):

1. Material Health, based on the X, gray, and P list to avoid harmful materials;
2. Material Reutilization, to eliminate waste and enable a circular economy;
3. Renewable Energy and Carbon Management, to assess both the embodied energy (as percentage from renewable sources) and carbon;
4. Water Stewardship, to avoid waste of water, and/or release of pollutants into water pool;
5. Social Fairness, to monitor equity in labour practices.

6.2.2 Regenerative design

Regenerative design (see also section 5.1) aims to overcome the sustainability concept by improving human health and the natural ecosystems and at the same time by reinforcing existing relationships or by creating new ones (M. Brown et al., 2020). For instance, with respect to the built environment, one of the most impactful economic sectors, regenerative design implies not only to improve building energy efficiency or material consumption but it also envisions innovative planning of entire neighbourhoods and cities to be more socially, culturally (Blerta Vula et al., 2018) and, of course, environmentally friendly and in balance with the surrounding natural ecosystem. On the contrary, currently policy-, decision-makers', as well as designers' answers simply tend to reduce environmental impacts or in the best case to off-set the impacts with compensation actions or with renewable energy production. Such an approach has been highly criticized by academics and practitioners to be inefficient and inadequate due to the urgent environmental and climate change issues (Wahl, 2016).

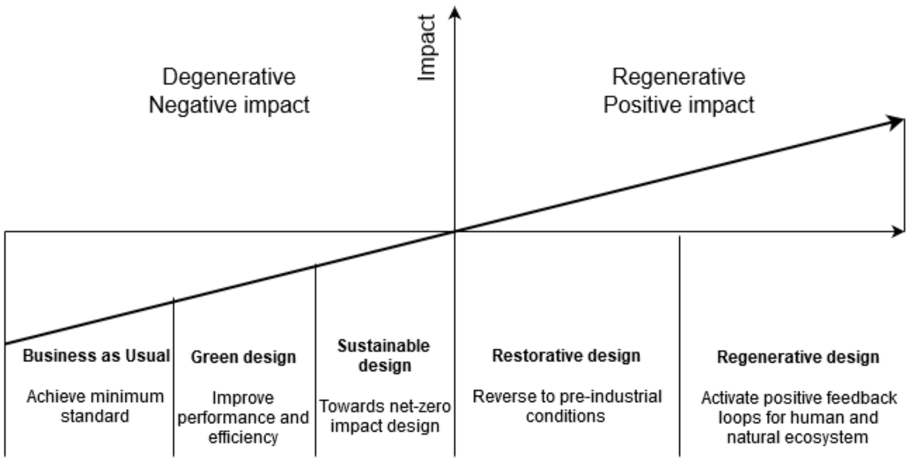


Figure 6.2: Sustainable, restorative and regenerative design definition. Adapted from Reed (2007) and M. Brown et al. (2020)

The term *"regenerative design"*, as many concepts related to environmental science, was first introduced in the sixties and in the seventies by Rodale (1972) referring to agriculture practices and then, two decades after, in the book *Regenerative design for sustainable development* written by Lyle (1996). Lyle defined a regenerative system as a system which *"provides for continuous replacement, through its own functional processes, of the energy and materials used in its operation"*. In the last decades, the term spread thanks to the studies of Raymond J. Cole and of Reed and many other academics and practitioners (Raymond J. Cole, 2012; Reed, 2007; Robinson et al., 2015). The shift in paradigm from the sustainability concept to a restorative approach and then towards a regenerative one is depicted and summarized in Figure 6.2. The sustainability approach aims to limit impact and it tends to a net-zero balance. The restorative points to bring back socio-ecological systems to an healthy state. Finally, the regenerative design objective is to maintain and to improve human health and the natural ecosystems at the same time (B. Martin et al., 2018). The paradigm shift sustainable-restorative-regenerative can be also seen as a shift in mentality from *Ego* to *Seva* through Eco practices (M. Brown et al., 2020). Ego refers to the past century approach. From the industrial revolution humankind dominated nature through technique and based the society on the exploitation of raw materials and resources in a linear fashion, i.e. the so-called *take-make-dispose* economic paradigm. In the past decades, the economic paradigm slowly moved from Ego mentality to an *Eco* approach mainly thanks to environmental economics contribution and to the spread of the *sustainable development* definition introduced globally by the Brundtland report (Brundtland et al., 1987). Finally, the shift towards Seva mentality, Selfless service from Sanskrit, well-represents the regenerative design practice where humankind is seeing itself as part of the natural ecosystem and not outside the Earth boundaries (M. Brown et al., 2020). In Sikhism, Seva represents a service/an action carried out without expecting a reward, i.e. a free gift, a complete *dedication to others* (Schlecker et al., 2013). In other words, regenerative design focuses on repairing/healing our sick world and the Seva mentality does it without expecting any reward. Regenerative design and CE thinking are intrinsically founded on system dynamics.

6.2.3 Performance economy

If producers retain
ownership of commodities,
today's commodities
will be tomorrow's resources
at yesterday's commodity prices.

Walter R. Stahel (2019, p.99)

The term *Performance Economy*, or *Functional Economy*, was conceived by Walter R. Stahel in 1986 and it refers to the performance/function of goods and services (CIRAIG, 2015, p.7). According to him, as reported by the EMF (2017), the performance economy should be intended as a general framework, based on four basic principles: long-life good, product-life extension, reconditioning activities and waste prevention. Together with the cradle-to-cradle school of thought, perhaps the performance economy represents one of the closest concepts to the current CE, and it is considered as a new business model where ownership should be retained directly by the businesses and producers, who should produce goods with an improved lifespan and a reduced environmental impacts, in terms of both energy and raw materials used (CIRAIG, 2015). Thus, as for the CE, the aim is to reduce the use of materials, energy (non-renewable), and the environmental impacts through a systemic approach where the products are not sold anymore to consumer at the point of sale as in the linear economy, but they are given in leasing, rented or dematerialized/digitized. Figure 6.3 shows schematically the main strategies of a Performance Economy, where the main focus is to sell performances or services. Walter R. Stahel (2019, p.39-42) subdivided the cycle of materials and

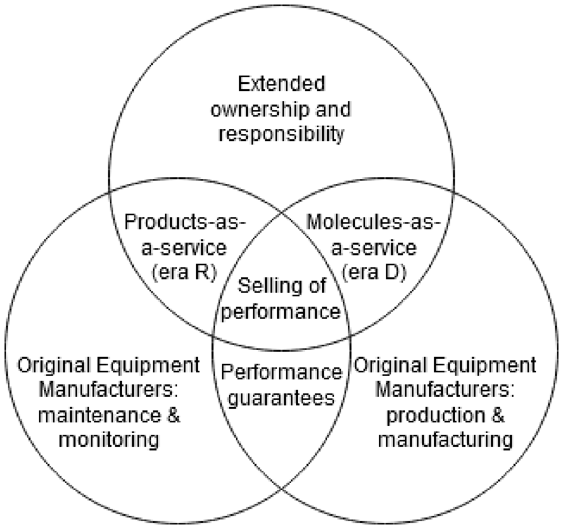


Figure 6.3: Performance Economy main focus representation. Adapted from Walter R. Stahel (2019, p.100).

products into two eras: 1) the *"era R"* (from reusing, repairing), the one focused on the products, and thus on business strategies to reuse, repair, and maintain them, and 2) the *"era D"* (from de-bonding), whose target is to recover molecules through recycling and other processes. In terms of policies and government taxes and laws, for Walter R. Stahel (2010, p.265-266) the strategy to adopt is straightforward: rewarding prevention of waste, CO_2 emissions, and other pollutants, adopting performance standards rather than product declarations, as well as incentivizing the extended producer responsibility. The performance economy can be easily summarized with the so-called sustainability triangle. The sustainability triangle generally is used to represent the 3 dimensions of sustainability (economic, social, and environmental impact). As described by Walter R. Stahel (2010, p.272-273), the sustainability triangle of the performance economy should reduce the ecological impact (e.g. the resource consumption) and meanwhile it should increase the social (e.g. jobs created) and the economic impact (wealth created), by internalizing the risk within the producer itself and preventing the waste production. The performance, then, can be evaluated through the *value-per-weight* and the *labour-per-weight* ratios. The former evaluate the wealth created per unit of resource used, while the latter refers to local jobs creation by reducing the use of fossil fuel, as envisioned in his milestone article *"The Potential for Substituting Manpower for Energy"* (W. Stahel, 1976).

6.2.4 Blue Economy

The Blue Economy proposed by the businessman G. A. Pauli (2010) in his book *The blue economy: 10 years, 100 innovations, 100 million jobs* (to be not confused with the *"Oceans Economy"* (Bennett et al., 2019; Golden et al., 2017; Smith-Godfrey,

2016) related to the exploitation and safeguard of oceans as defined during United Nations Conference on Sustainable Development in 2012 (UNCTAD, 2014)) is an open-source movement (EMF, 2017) based on 21 nature-based principles (G. Pauli, 2016) founded to inspire innovative business models to overcome the *do less bad* philosophy rooted into the green economy (G. A. Pauli, 2010). The Blue economy aims to enable abundance starting from local resources, in order to develop innovative solutions both environmentally-friendly and economically and socially profitable and advantageous. As already stated by the C2C philosophy, it aims to eliminate waste (*"Natural systems cascade nutrients, matter and energy – waste does not exist. Any by-product is the source for a new product"*), and to enrich biodiversity and product diversity (*"Nature evolved from a few species to a rich biodiversity. Wealth means diversity. Industrial standardization is the contrary"*), by promoting industrial symbiosis and the complexity of ecosystems (*"In natural systems everything is connected and evolving towards symbiosis"*), and a regenerative design approach (*"In Nature negatives are converted into positives. Problems are opportunities"*) (G. Pauli, 2016).

6.2.5 Industrial Ecology

The industrial ecology may be traced back to the second half of the nineteenth century. In 1879, Alfred Marshall coined the term *industrial district* in his book *Principles of economics* to describe clusters of firms and industries grouped in the same geographical area. Thus, the idea of industrial symbiosis and materials and products exchanges among industries to improve production efficiency is quite old. After almost a century, just after the end of the 2nd World War in 1947, Renner (1947) discussed the opportunity for firms and industries to also exchange waste as raw materials. The first documented case study of industrial symbiosis dates back to the sixties, the so-called Kalundborg district in Denmark (Y. Zhang et al., 2015) . The Kalundborg district[1], composed of 6 private partners, 3 public ones, and 25 different streams (water, energy, material), has been largely studied in past decades (EMF, 2020). It was first cited by Valdemar Christensen in 1989 who coined the term *industrial symbiosis* to describe it (Y. Zhang et al., 2015). Symbiosis (from Greek, living together), introduced by Anton de Baryin in the nineteenth century, was previously used in biology (Darlington, 1951) to describe the mutual benefit between two, or more, living creatures (Oxford dictionary, 2020):

> **Definition 6.2.1 — Symbiosis.** The relationship between two different living creatures that live close together and depend on each other in particular ways, each getting particular benefits from the other

In the same years, instead, Robert U. Ayres et al. (1994) introduced the term *industrial metabolism*, i.e. the sum of all input (energy, materials, water, ...) streams and all the output (waste, by-products, ...). The term *metabolism*, initially adopted by German psychologist, was introduced in 1815 to describe the human metabolism related to the material exchanges during respiration (Robert U Ayres and L. Ayres, 2002, p.17). Over a century, the concept of metabolism has been adopted by completely different fields like chemistry or biology (Bing, 1971), and, then, by environmentalist (E. P. Odum

[1] `http://www.symbiosis.dk/en/` (Symbiosis, 2020)

et al., 1971), sociologists and economists. Marx and Engels were the first to apply the term metabolism to the society in order to discuss the exchanges between human and Nature (Robert U Ayres and L. Ayres, 2002, p.18). In 1989, Frosch et al. (1989) in their article "Strategies for manufacturing" coined the term *industrial ecosystem*. The transition to Industrial Ecology is attributed properly to Frosch et al. who stated *"the traditional model of industrial activity in which individual manufacturing processes take in raw materials and generate products to be sold, plus waste to be disposed of- should be transformed into a more integrated model: an industrial ecosystem. The industrial ecosystem would function as an analogue of biological ecosystems."* Thus, since the eighties, the idea of closing the loop and of circularity of materials has been at the core of Industrial Ecology (IE) (Erkman, 1997). In 1992, during a conference in Colorado, organized by the Interdisciplinary Earth Studies Global Change Institute on the Carbon Cycle, the term industrial ecology was coined, as reported by Socolow et al. (1997). In those years, a largely accepted definition was given to industrial ecology (T. Graedel and Lifset, 2016; Richards et al., 1994):

> **Definition 6.2.2 — Industrial Ecology.** Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of those flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources

Basically IE has to be intended as a framework/procedure and not properly as an assessment tool. Indeed, the IE application relies on the use of Life Cycle Assessment analysis (ISO, 2006a), Input-Output Tables (W. Leontief, 1986), or on Material Flow Analysis (MFA). MFA is a methodology to assess stocks and flows of material for a particular process, or region under study (T. Graedel and Lifset, 2016). Specific flow analysis for single materials are denoted as *substance flow analysis* (SFA). The first MFA study has been conducted by Robert U Ayres and Rod in 1986 to assess the emissions related to metal processing in the New York region (Robert U Ayres and Rod, 1986). In the following decade, the MFA concept has been expanded towards the so-called *socioeconomic metabolism* (T. Graedel and Lifset, 2016), adding in the analysis also social aspects. This evolution brought to the first national material flows (Adriaanse et al., 1997) and to the introduction of the *economy-wide material flows* analysis (T. Graedel and Lifset, 2016). From national MFA, in the last decades, several statistical indicators emerged such as the domestic material input (DMI) or the domestic material consumption (DMC), currently used and adopted, for instance, by EUROSTAT (Fischer-Kowalski et al., 2011), as discussed in the chapter 3. The use of the input-output tables (IOTs) for national MFA studies is also quite common thanks to the introduction of the so-called environmental IOT (EIOT) and physical IOT (PIOT) (Lave et al., 1995), which take into account the emission and the material exploitation per economic sector, respectively. The IOT will be described more in detail in the next chapter.

6.2.6 Biomimicry

Nature runs on sunlight.
Nature uses only the energy it needs.

Nature fits form to function.
Nature recycles everything.
Nature rewards cooperation.
Nature banks on diversity.
Nature demands local expertise.
Nature curbs excesses from within.
Nature taps the power of limits.

Janine M. Benyus
(Benyus, 1997, p. 7)

Biomimicry (from the Greek bios, life, and mimesis, imitation), as conceptualized by Janine Benyus in her brilliant book *Biomimicry*, may be summarized as *"innovation inspired by the nature"*. Biomimicry is a new discipline, officially introduced in 1997, where we *learn* from nature, instead of *extract* from nature. Indeed, in the past centuries, the *Homo Industrialis* reached the limits of the nature's tolerance and, according to her powerful words, there is a need for a Biomimicry Revolution (Benyus, 1997, p.2):

> *"In a society accustomed to dominating or improving nature this respectful imitation is a radically new approach, a revolution really. Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her."*

Thus, nature is the guide to follow because, again with her words (Benyus, 1997, p.3), *"after 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to survival"*. In brief, according to Kennedy et al. (2015) statement, biomimicry may be defined as an emulating process:

> **Definition 6.2.3 — Biomimicry.** Learning from and emulating biological *forms*, *processes*, and *ecosystems* tested by the environment and refined through evolution ... and (it) can be applied to solve technical and social challenges of any scale.

Although Benyus has been undoubtedly recognized as the founder of the biomimicry school of thought, the origin of the idea traces back to Otto Herbert Schmitt who introduced the term *"biomimetics"* to delineate the knowledge-transfer process of technology innovation by learning from biology (Harkness, 2002). Born in 1913, he spent his bachelor and master degree among three departments - physics, zoology, and mathematics - fulfilling his multidisciplinary behaviour. In his Ph.D. thesis, he developed his first example of biomimetic technology, i.e. an electronic device, by reproducing the propagation of action potentials through nerves. In his career, he focused in biophysics and bioengineering, and only nearly at the end he developed the biomimetic concept (Harkness, 2002). The first use of the word, may be in the paper "Some interesting and useful biomimetic transforms" discussed in 1969 during the *"Third International Biophysics Congress in Boston"* (Schmitt, 1969). Despite its huge research potential, it's only thanks to the contribution of Benyus that biomimicry gained momentum: in the first decade of the new century, biomimicry researches, and applications increased outstandingly. Biomimicry fully falls into the foundations of the CE, overlapping with other schools as the regenerative design of Lyle (1996) or the Blue Economy of G. A. Pauli (2010). It offers a methodological approach to redesign product, processes, and ecosystems by imitating biological designs, which can be considered *"resilient, adaptable, multifunctional, regenerative, and generally zero-waste"*, and, as the regenerative design, together with design thinking, it could support the overcoming of the anthropocentric view (Kennedy et al., 2015). Despite its potential, critics highlight that a biomimetic solution is not always environmentally better in terms of efficiency, impacts, and other critical aspects for sustainability (Reap, Baumeister, et al., 2005). For this purpose, a biomimetic application should focus on three hierarchical levels - 1) forms, 2) processes, and 3) systems - to fulfil the sustainability principles (Baumeister et al., 2011). The form level aims at reproducing the shape and related functionalities, while the process level refers to how Nature manufactures. In terms of processes, nearly all biological materials are assembled at atmospheric pressure and ambient temperature by combining only six chemical elements: carbon, hydrogen, oxygen, nitrogen, phosporous, and sulfur. At the system level the functioning of an object, or a process, is taken into account considering the more complex relationships with the surrounding environment. Indeed, focusing only on forms or processes, does not ensure better environmental performance (O'Rourke, 2013), as also pointed out by the most recent Organizational LCA (International Organization for Standardization, 2014). The development of the biomimicry at the system level is, without any doubt, the most fundamental step in emulating Nature, as demonstrated by the interest of the Defense Advanced Research Project Agency (DARPA) in developing *neurotechnology* solutions for robotics (Alan et al., 2002; Ortalli et al., 2010; Passino, 2005).

Biomimicry is not only fascinating for its useful applications and insights. Differently from other schools of thought, biomimicry cannot be reduced to some economics principles, efficient management approaches, assessment methodologies, or design tools. The concepts and principles introduced by biomimicry go much farther and, in recent years, have been discussed in philosophical and ethical terms as well (Dicks, 2016). As conceived by Benyus, it is built upon three basic principles (Benyus, 1997):

1. *Nature as a model*. Nature should be analyzed, understood, and imitated to solve human problems.
2. *Nature as measure*. Nature is right, knows what works and what lasts.
3. *Nature as mentor*. What can we learn from Nature?

Dicks (2016) defined the Biomimicry as a new philosophical paradigm, named as *Enlightened Naturalism*, and he described the three statements of Benyus in terms of the poetic, the ethical, and the epistemological principles. The poetic principle, *Nature as a model*, refers to the "bringing forth" or "production" of things (poiesis), while *Nature as a measure* and *Nature as a mentor* are respectively the ethical and epistemological principles. Indeed, Nature sets the ethical boundaries and limits of what is just and what is not (thus, Nature as a measure), and, at the same time, Nature defines the truth and wisdom, free of error (thus, Nature as a mentor). Seeing Nature as model, measure and mentor, in the author's opinion is deeply different from past philosophical paradigms, as Christianity, modern humanism, and postmodern relativism, which identified God, man and beings, respectively, as the object of model, measure, and mentor. In Christianity (see focus 6.3 for the latest debate about Christianity), for instance, God is the model, i.e. man image is based on God image, the measure of just and right actions, and the mentor, the source of truth on Earth, while in modern humanism the man itself is the source of imitation (model), ethical limits (measure), and truth (mentor). Thus, mans become mentor for other mans and set the ethical values. In postmodernism, instead, the focus is shifted to *"actual entity"*, as used by Whitehead (Harman, 2007; S. E. Hooper, 1941) or to the *"actants"*, as defined by Latour (1993), to refer to God, humans, or any other beings, living or non-living. Using the word of Harman (2007), referring to Bruno Latour post-modern philosophy:

> *everything that exists can be regarded as an actor or actant. Whether it be 'a storm, a rat, a rock, a lake, a lion, a child, a worker, a gene, a slave, the unconscious, or a virus,' all objects in the cosmos are on the same footing. There is no privilege for a unique human subject, imprisoned in its faulty representations of a world that may or may not exist. Instead, you and I are actants, Immanuel Kant is an actant, and dogs, strawberries, tsunamis, and telegrams are actants. With this single step, a total democracy of objects replaces the long tyranny of human beings in philosophy.*

Focus 6.3 — Laudato si.

Praise be
to you, my Lord,
through our Sister, Mother Earth,
who sustains and governs us,
and who produces various fruit
with coloured flowers and herbs

Francesco D'Assisi

The 24th of May 2015 Pope Francis publicly released his second encyclical, named *Laudato Si. On care for our common home* (Pope Francis, 2015). The name of the encyclical derives from the *Canticle of the Creatures* of Saint Francis of Assisi, a prayer to thank God for all the creatures on Earth. In the Laudato Si encyclical Pope Francis interconnect the current environmental crisis with the social crisis of humanity, invoking for an *integral ecology* for a sustainable development. Recalling the words of his predecessor Benedict XVI, he sent an invitation to everyone for *eliminating the structural causes of the dysfunctions of the world economy and correcting models of growth which have proved incapable of ensuring respect for the environment*. In the encyclical, he discussed current global issues such as pollution and climate change, the loss of biodiversity, as well as the global inequalities and injustices, defining *"the climate is a common good, belonging to all and meant for all"*. Similarly to the Posthuman philosophy and Biomimicry, he invoked for a *mutual responsibility between human beings and Nature.* The Laudato Si, deeply rooted on sustainable development principles, asked that each community does not overexploit the earth and nature taking only what is needed for subsistence and ensuring prosperity for next generations. *The earth is the Lord's*. Criticising the modern anthropocentrism, as in biomimicry thought, Pope Francis wrote

> *the technological mind sees nature as an insensate order, as a cold body of facts, as a mere 'given', as an object of utility, as raw material to be hammered into useful shape; it views the cosmos similarly as a mere 'space' into which objects can be thrown with complete indifference.*

Hence, as in posthuman theory, he stated

> *Nature cannot be regarded as something separate from ourselves or as a mere setting in which we live. We are part of nature, included in it and thus in constant interaction with it.*

Finally, the ecological crisis cannot be face only by taking care of our Earth but social injustice must be addressed as well; continuing

> *the present ecological crisis is one small sign of the ethical, cultural and spiritual crisis of modernity, we cannot presume to heal our relationship with nature and the environment without healing all fundamental human relationships.*

■

In Biomimicry the focus is shifted to Nature as the unique entity to be seen as model, measure, and mentor. *Model* because Nature is the source of inspiration and imitation. According to Benyus (1997), "Biomimicry is a new science that studies nature's models and then *imitates* or *takes inspiration* from these designs and processes to solve human problems". Such a statement, in Dicks's opinion, should be intended in the Aristotle's meaning of *mimemis*, i.e. a creative process which create a *new composition not found in Nature*, rather than in Plato's one, i.e. a degraded copy of the model (with a consequent loss of information) (Dicks, 2016). *Measure* because *"after 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts"* (Benyus, 1997). Thus, Nature provides the laws that need to be followed, and, at the same time, the limits and the boundaries not to overpass (i.e. the planetary boundaries). According to Dicks (2016), within this new philosophical framework, *"these limits should not be seen as unfortunate restrictions on our freedom, but rather as powerful sources of creation and, as such, ultimately generative of different types of freedom"*, in the same way that poetry gives boundaries and limits in forms to writers but unleashes a new form of creativity. Finally, *mentor* because, in Benyus thought, we should *learn* from Nature. In this sense, Nature should be intended as the source of wisdom and knowledge, rather than the man itself as in modern humanism and postmodern philosophies.

Concluding, biomimicry could provide the fundamental laws and rules for an emerging paradigm related to the Circular Economy, not only in philosophical terms. First, *Nature as a model*, in its broadest meaning, should be intended at planetary scale and not only as source of inspiration for design innovation. At planetary scale, Nature works in cycles, in biogeochemical cycles, and it recycles and reuses everything. Second, *Nature as a measure* gives the limits, the biogeochemical limits, as described by Raworth (2017) and Rockström, W. L. Steffen, et al. (2009). Third, *Nature as a mentor* means that man should start to think according to the Natural rules, both in terms of cycles and limits, and not anymore in terms of the rational man, the homo *oeconomicus*. To do so, the first step is to point out which are the planetary boundaries under which a dynamic eternal balance should be envisioned. The nine planetary boundaries identified - climate change, rate of biodiversity loss, interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global fresh water use, change in land use, chemical pollution, and atmospheric aerosol loading - are summarized in Table 6.1. The thresholds have been identified for seven of the nine boundaries, excluding chemical pollution and atmospheric aerosol with respect to pre-industrial values or to assimilative capacity of the environment. In particular, the thresholds have been set by analysing the average concentration during the Holocene in order to identify the lower and upper values of a *zone of uncertainty* where unpredictable changes may occurs. Thus, the lower boundary has been selected as planetary boundary for the chosen control variable. Within their analysis Rockström, W. Steffen, et al. (2009) pointed out how three - i.e. climate change, rate of biodiversity loss, nitrogen cycle - out of the nine boundaries already surpassed the identified threshold. Focus 6.4 summarizes the main limits of the Planet and their rationale.

Focus 6.4 — Planetary boundaries. The idea of the planetary boundaries, in its broader meaning, can be traced back to the Sixties and the already discussed article of Boulding (1966) on “The economics of the coming Spaceship Earth” who introduced the concept of the Earth as a closed system. This rough concept remained undeveloped until 2009 when on a milestone article on Nature titled “A safe operating space for humanity” Rockström, W. Steffen, et al. (2009) proposed nine main planetary boundaries and relative control variables. The authors introduced the nine boundaries by looking at historical trends for the main biogeochemical cycles on Earth, as well as other, apparently unrelated, aspects as biodiversity loss rate or change in land use. In their opinion, the nine boundaries are necessary to maintain, with certainty, the entire world within the Holocene geological epoch which has allowed humanity to thrive in the past 10,000 years (P. J. Crutzen, 2016), avoiding to enter in the so-called new Anthropocene epoch, as defined by P. Crutzen et al. (2000), and to cause sudden and unpredictable changes. Indeed, without human pressure on Nature, the current geological epoch, i.e. the Holocene, should last for thousands of years (Berger et al., 2002), while overpassing one, or more, of these limits could affect the entire world by changing some natural mechanisms and processes which maintain the Earth in a stable state, as the indian monsoon or the melting of Greenland ice sheet (Lenton et al., 2008; Scheffer et al., 2001).

The boundaries can be classified into “rapid” and “slow” planetary processes. The former, in particular, consist of three boundaries - climate change, ocean acidification, and stratospheric ozone depletion - referring to such processes which can induce a sudden change, as the Greenland ice melting, when a threshold is exceeded (e.g. radiative force, or ozone depletion), while the latter consists of processes for which no precise consequences may be predicted but are mainly related to the resilience of the Earth system as a whole and may deeply affect others biogeochemical cycles (e.g. the ocean acidification may slow down the property of ocean to act as a carbon storage system).

With respect to the rapid ones, one threshold has already been surpassed (climate change) while another one (ocean acidification) is very near to the identified limit. Climate change, which counts two control variables (CO_2 concentration and change in radiative forcing as both can induce the rise of global temperature and Greenland ice melting), exceeded the atmospheric CO_2 concentration while the radiative forcing is still below the threshold. Ocean acidification, instead, is strongly related both to the capacity of the ocean to stock the CO_2 emissions and to the safeguard of the marine biodiversity (thus on the rate of biodiversity loss boundary) because of many organism are susceptible to a change in the pH of water (due to the carbon concentration in water). The threshold is calculated in term of the concentration of aragonite, a carbonate mineral ($CaCO_3$), in the surface sea water and currently it is close to the set threshold. Its effect may cause a drastic loss in marine biodiversity since many organism shells, made of calcite, could dissolve into the water if the Ω_{arag} falls below one (Fabry et al., 2008). Stratospheric ozone depletion is a typical example of a successful coordinated human effort to solve a dangerous environmental issue globally, and currently such limit is below the defined threshold. Stratospheric ozone is responsible for filtering the ultraviolet radiation reaching the Earth, which if not filtered by Ozone may strongly affect human health and Antarctic ice melting. This issue has been officially recognized and faced in the Eighties, when, thanks to the Montreal Protocol (UNEP, 1987), the production of the main known substances, mainly Chlorofluorocarbons (CFCs), causing the depletion of the Ozone layer have been stopped. Recently also the hydrofluorocarbons (HFCs) have been targeted. Generally, the Ozone depletion is measured in Dobson Unit (DU), introduced by Gordon Dobson at the begin of the XX century as the thickness of the Ozone layer in air column at Standard Conditions for Temperature and Pressure, and it can be measured in stratospheric O_3 concentration.

Regarding the limits correlated to "slow" global processes, two out of six boundaries (four if only the defined ones are taken into account) have been already surpassed (i.e. rate of biodiversity loss and nitrogen cycle). The nitrogen and phosphorus cycles, although measured distinctively, are both directly responsible for Eutrophication, or nutrient enrichment. According to D. M. Harper et al. (1992, p.2) eutrophication *"is the term used to describe the biological effects of an increase in concentration of plant nutrients - usually nitrogen and phosphorus, but sometimes others such as silicon, potassium, calcium, iron or manganese - on aquatic ecosystems"*. Nitrogen, as well as phosphorus, may deeply modify ecosystems, primarily marine and aquatic ones, inducing overgrowth of biomass and plants due to the nutrients released into the environment. The nitrogen in the environment is primarily generated by industrial and agricultural fixation of ammonia from atmospheric nitrogen (about 80 and 40 Mt N yr^{-1} respectively) or by fossil-fuel and biomass combustion (about 20 Mt and 10 N yr^{-1} respectively). Currently, the corresponding boundary has been exceeded by about four times: the proposed boundary corresponds to 35 Mt N yr^{-1}, while the annual global production of nitrogen (amount extracted from the atmosphere) reached more than 120 Mt yearly. Phosphorus, which is a finite mineral, induces similar effect on the environment by inducing the overgrowth of biomass. Although global phosphorus use and production have steadily increased in the past century (nowadays more than 8-9 Mt P yr^{-1}) the limit (about 11 Mt P yr^{-1}) has not yet surpassed and prediction estimated that more than 10,000 years - the P cycle timescale is in the order of 10,000 years (Lenton et al., 2008) - are needed to double the amount of phosphorus into the ocean (Rockström, W. L. Steffen, et al., 2009).

Rate of biodiversity loss (together with climate change and the nitrogen cycle) is the third limit, globally surpassed. Accordingly to Chapin Iii et al. (2000), the actual rate of extinction represents the sixth mass extinction in the history of the Earth. The loss in biodiversity has difficult prediction on global stability, but it can strongly affect the resilience of natural ecosystems with unpredictable consequences. The proposed boundary is based on the average extinction rate during the Holocene and it consists of 10 extinctions per million species-years (E/MSY), which has been largely exceeded (currently the average rate is greater the 100 E/MSY) (Rockström, W. L. Steffen, et al., 2009). Finally the two last measurable boundaries - i.e. global fresh water use, and change in land use - are directly related to human needs (in terms of space and food). An excessive fresh water use and possible consequent lack of water, beyond the direct implication for human purposes and needs, is directly correlated to the safeguard and stability of local ecosystems. Indeed, one every four river basins is estimated not to be able to reach the oceans because of lack of available water causing problems for acquatic and terrestrial life. Moreover, the over-consumption and exhaustion of the so-called *blue water* - i.e. water pools directly related to human water supply - affects indirectly the *green water* - i.e. the soil moisture and corresponding water flows - interrupting a stable water cycle and eventually causing the desertification of lands. Although water consumption should be analysed locally, the global threshold has been estimated to be around 4000 $km^3 yr^{-1}$ (Oki et al., 2006) which can be enough to satisfy human needs (currently global freshwater use is around 2600 $km^3 yr^{-1}$) (Shiklomanov et al., 2004). Finally, with respect to the use and exploitation of land, a threshold corresponding to 15% of ice-free land surface has been chosen (currently humanity use around 12% of total ice-free land surface) to guarantee a safe space for humanity without threatening local ecosystems (Rockström, W. L. Steffen, et al., 2009). ■

As Biomimicry philosophical discussion highlighted, citing directly Rockström, W. L. Steffen, et al. (2009) *"the thresholds in key Earth System processes exist irrespective of peoples' preferences, values..."*. Thus, it is fundamental to go deeper on the assimilative capacity of the Earth system, and not only to define a control variable to monitor a certain boundary. Indeed, in the authors' opinion, the approach based on planetary boundaries mainly relies on the capacity of the environment to sustain human economy, and, thus, on human-environment interaction, and sustainability science, and on the understanding of the functioning of natural system complex dynamics and self-regulating feedbacks (Rockström, W. L. Steffen, et al., 2009).

Table 6.1: Planetary boundaries and thresholds. Adapted from: Rockström, W. Steffen, et al. (2009) and Rockström, W. L. Steffen, et al. (2009).

Earth-system process	Parameters	Unit of measure	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration	ppm	350	387	280
	(ii) Change in radiative forcing	Wm^{-2}	1	1.5	0
Rate of biodiversity loss	Extinction rate	E/MSY	10	>100	0.1–1
Nitrogen cycle	Amount of N_2 removed from the atmosphere for human use	$MtNyr^{-1}$	35	121	0
Phosphorus cycle	Quantity of P flowing into the oceans	$MtPyr^{-1}$	11	8.5–9.5	$\sim$1
Stratospheric ozone depletion	Concentration of ozone	DU	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	Ω_{arag}	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans	km^3yr_{-1}	4	2,6	415
Change in land use	Percentage of global land cover converted to cropland	%	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined			
Chemical pollution	E.g. Concentration of persistent organic pollutants in the environment.	To be determined			

6.2.7 Environmental Economics

The complex human-environment interaction, in terms of human pressure on nature and natural assimilative capacity, is under study since the Sixties when the environmental economics (EE) and other research fields (e.g. environmental sociology) emerged. The history of EE traces back to the XVII-XIX century and the earlier decades of the XX century. Environmental economics emerged as a convergence of several previous schools of thoughts and knowledge fields, from the classical/neoclassical or humanistic economics to physical natural sciences (Pearce et al., 1990, p.3-28). From classical political economy the heritage was mainly related to the basic rules of interactions and visions about possible future states for the economic system. Growth in classical economics generally was interpreted as a transitory phase toward a final stationary state; in the long-run, fathers and founders of classical political economy as Thomas Malthus and David Ricardo generally looked at growth in a pessimistic way, because originally technology advances were not included in their model. Indeed, in their opinion, environmental limits (mainly linked to agricultural land surface) inevitably bring humanity to the so-called Malthusian catastrophe due to Ricardian scarcity, stopping population growth due to food supply scarcity. In the Marxist theory, instead, progress was partially taken into account and seen as technological development allowed by *humanizing* (exploiting) Nature and, with the *labour theory of value*, the workers were the only generators of the economic profit, but, in Marx opinion, the economic system fails the so-called *reproduction test*, i.e. according to Pearce et al. (1990, p.8-9) *"a viable basis for any society can only be provided if the system of production is capable* *of reproducing itself"*. Pearce et al. interpreted this aspect as the *material balance*, they introduced in the Nineties. At the end of the XIX century, neoclassical economy abandoned the theory of labour and moved to the modern supply and demand rules where commodity's price mainly depends on its scarcity. Inspired by Newtonian laws, neoclassical economists described the human economy with a mechanistic point of view based on rational individuals who desire to maximize their utility. In this framework, the *"basic theorem of welfare economics"* proved that a competitive market moved towards the *Pareto optimum*, i.e. a state where none can improve satisfaction/profit without reducing someone else satisfaction (Shen, 2018). In such cases, when the market cannot maximize collective utility and welfare, the so-called *market failures*, government interventions may adjust the failures (Pearce et al., 1990, p.11). Because of the two World Wars and large generalized unemployment, government intervention theories evolved and became mainstream, although highly criticized, with the fundamental contribution of John Maynard Keynes . Although worldwide recognized, basic theorems of neoclassical school of thought introduced several simplifying assumptions (perfect information and rationality, independence of consumers, no externalities, ...), and later on they have been highly criticized and debated. For instance, thinkers related to the *humanistic paradigm* introduced a behavioural approach to consumers, focusing more on a *hierarchy of needs*, as previously discussed recalling Rovers (2019), instead of completely substitutable goods. In the Sixties, the discussion about the extension of the boundaries of the economic models (i.e. planetary boundaries, depletion of resources) and the main underlying idea of the rational economic individuals were dominated by four main *world views* as summarized in Table 6.2, basically grouped into technocentric and ecocentric. The thought of the former group - i.e. cornucopian and accommodating schools of thought - is based on the idea that technology improvement may solve the main environmental problems (e.g. Rifkin) while the latter group - i.e. communalist and deep ecology schools - mainly aims and points at preserving resources and natural ecosystems, also identifying right and duties for non-human species (e.g. Carson). Generally, the technocentric group gives an *instrumental* value to Nature, i.e. an extractive value, while the ecocentric group recognized an *intrinsic value* in Nature and in its preservation.

Table 6.2: Main world views related to human-environment interactions. Adapted from Pearce et al. (1990, p.14)

Classification		Description
Technocentric	Cornucopian	Growth-oriented, resource exploitation can be ensured through technological innovation
	Accommodating	Resource conservationist, sustainable development
Ecocentric	Communalist	Resource preservationist, necessity of local socio-economic systems to ensure sustainability
	Deep Ecology	Extreme preservationist, economy based on organic agriculture and deindustrialization.

The rise of the environmental economics was supported by several paradoxes which undermined the stability of neoclassical economics and previous theories. For instance, just to name a few, the *Easterlin's paradox* revealed how individual happiness and economic growth are not correlated (Clark et al., 2008), or the *Hirsch's positional goods* which highlighted inequality and how many goods are available only to a minority group (M. Schneider, 2007). On top of these paradoxes and open questions, different approaches were introduced to face the main limits of the Earth. A relative and an absolute approach was the way to consider the environment into economic and policy analyses. The relative one, i.e. cost-benefit analysis (CBA), evaluated pollution and externalities to the environment as a costs to be balanced while the absolute one, i.e. fixed standard approach, sets general standard and constraints for the exploitation of the environment (e.g. the use of lands, generation of pollution, ...). This type of analysis and the boundaries related to the human-environment interactions in the economic system brought economists, political scientists and philosophers to question the assumptions of the economic models, especially regarding individual preferences and utilities, as well as how to valuate the environment itself (Pearce et al., 1990, p.20-22). According to Pearce et al., within the environmental economics literature there are three basic values which should be addressed: 1) individual, 2) public and collective, and 3) physical ecosystem preferences and values. The first point regards the classical object of economic theory, the second social norms and the third one the Earth and ecosystem constraints. In particular, the latter, i.e. the physical values of the ecosystem, has found its expression in the *"existence theorem"* which is currently the main limitation of current economic models. The existence theorem *"guarantees that any economic optimum is associated with a stable ecological equilibrium"* (Pearce et al., 1990, p.24). Thus, as previously discussed in focus 6.4 discussing the planetary boundaries, at the global level it is fundamental to understand the main biogeochemical cycles which rules the whole Earth.

6.2.8 Other concepts

Concluding, according to *Cicular Economy: a critical literature review of concepts* (CIRAIG, 2015), other relevant concepts related to the CE are *sustainable development* (see section 5.1), *green economy* and the *ecological transition* (see chapter 2 and 3), *extended producer responsibility*, *life cycle thinking* and *eco-design*. For the sake of completeness, I briefly report the fundamentals and basic definitions of *extended producer responsibility*, *life cycle thinking* and *eco-design*, as well as of *bioeconomy* and *collaborative economy*.

The *extended producer responsibility* (EPR), according to the OECD (2020), is:

> **Definition 6.2.4 — Extended producer responsibility.** An environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle.

Generally based on the "polluter pays" principle, the EPR framework highlights the informative responsibility, i.e. who (which stakeholders) is in charge of exhaustively informing final users/consumers or other stakeholders of the product supply chain (Lindhqvist, 2000). EPR policies could be intended as the arm of governments for circular strategies in order to push businesses to follow certain eco-design principles, or to force companies to redesign their supply chain in order to close the product/material loop.

The *life cycle thinking* (LCT) is a holistic point of view to analyse the whole life cycle of products and processes. LCT emerged as an approach mainly due to sub-optimal environmental and economic, solutions when only a single phase of a product life was considered. Indeed, optimizing a single step of the production process (or EoL for instance) of a product/process does not necessarily imply a better environmental performance if the whole process is considered (CIRAIG, 2015). The primary tool to assess the life cycle impact of products/services is the Life Cycle Assessment (LCA), currently considered the most complete and efficient instrument to assess environmental impacts (Bjørn et al., 2013). LCA LCT, and design principles will be treated in more detail in chapter 7.

The *eco-design* aim, broadly speaking, is very close to CE aim, i.e. closing/narrowing the loop, and may be considered as the way of taking into account the environmental impacts in early design stage (CIRAIG, 2015). In general terms, eco-design can be defined as (Karlsson et al., 2006; Luiz et al., 2016; Conrad Luttropp et al., 2006):

Definition 6.2.5 — Eco-design. The integration of environmental considerations into product development.

Thus, the scope of eco-design is to avoid negative impacts of products during the design phase. Indeed, it has been estimated that more than the 70% of environmental impacts can be avoided during the design phase (Knight et al., 2009; Yarwood et al., 1998). Conrad Luttropp et al. (2006), in fact, stated that eco-design tools are like a *"swiss army knife"*, even if eco-design should be considered as an analytical approach, not as a tool itself, which can be based on the adoption of other tools such as life cycle assessment, or environmental product indicators.

The *Bioeconomy* can be defined as (McCormick et al., 2013)

Definition 6.2.6 — Bioeconomy. An economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources, such as plant and animal sources.

Bioeconomy, mainly referred to the biological cycle of the Butterfly diagram, constantly grew in the last two decades and is seen as a promising research field and economic sector in order to reduce GHG emissions and fossil fuel exploitation. Three main sub-fields have been envisioned, related to bio-technology, bio-resources and bio-ecology. The first two focus on the impact of biotechnology in healthcare, as well as on the production of biofuels or on processing organic materials in order to gradually substituting raw materials, while the latter aims at optimizing the use of energy and nutrients meanwhile promoting biodiversity and restoring/regenerating natural ecosystems (Bugge et al., 2016).

The *Collaborative Economy*, together with the bioeconomy, had, and will have a huge impact on the labour market, as well as on the environmental impact generated by the economy. The Collaborative Economy, also named *sharing economy*, *gig* or *peer* *economy*, is defined as an economy that allows consumers to access to *under-utilised assets* (Petropoulos, 2017). The term, in a broader meaning, may also refer to second-hand markets and decentralised networks. Indeed, it has been also defined as (Botsman, 2015)

> **Definition 6.2.7 — Collaborative Economy.** An economic system of decentralised networks and marketplaces that unlocks the value of underused assets by matching needs and haves, in ways that bypass traditional middlemen.

6.3 Circular Economy: relabeling or new paradigm?

The text of this section is largely based on and adapted from the inproceeding "Circular economy: new paradigm or just relabelling? A quantitative text and social network analysis on Wikipedia webpages" (Dario Cottafava, Ascione, and Allori, 2019).

Despite the steep growth in Scopus[2] publications (around 350 in 2016 and more than 1'000 in 2018) and consultancy reports related to the CE, as well as the attention received from policy and decision-makers (Tennant et al., 2015), critics hold that blurriness about CE occurs because the paradigm operates in significantly diverse schools of thought (see section 5.5 and section 6.2). Much of the blurriness is generated by the different fields which involve CE as well as by an overlapping with the wider issue of Sustainability. Some authors tried to overcome the blurriness around CE through bibliometric analysis (D'Amato et al., 2017; Geissdoerfer et al., 2017; Homrich et al., 2018) and systematic literature reviews (Merli et al., 2018). Although these studies resulted in an increased transparency about the CE, they could not provide any information on the linkages among the underlying concepts.

Starting from the research question *"Is Circular Economy a new paradigm or just a relabelling of old knowledge?"*, this work would support the definition of the boundaries of the CE and the analysis of the relationships between different disciplines and spheres of knowledge. To accomplish this task we use an innovative methodology, based on Chiarello et al., 2018, which consists of three main steps: 1) extraction of a seed list of relevant keywords related to the CE from Scopus, 2) construction of three networks (a general, a technology and a field-related one), and 3) analysis of the networks thanks to the Social Network Analysis. The key features of this approach mainly rely on: 1) the interconnection and linkages among the analysed concepts and keywords, 2) the independence from expert opinion and from the time when the analysis is performed (as Wikipedia is not affected by transient hype), and 3) the boundaries of Circular Economy are defined endogenously (i.e. as an emergent feature of the network itself).

This section is structured as follows. Section 6.3.1 provides an overview of CE results in Scopus and about Wikipedia as a data source. In Section 6.3.2 the methodology used in this research work is presented in detail. In Section 6.3.3 the results are presented and discussed. Finally, section 6.3.4 acknowledges the limitations and the hints for further research.

[2] Scopus is one of the largest database for scientific contributions

6.3.1 Introduction

The query “Circular Economy”[3] in Scopus generated 4’583 results, depicting an upwards trend in the production of papers from 2010 to 2018. In 2010, for instance, papers produced about CE were just 154, while in 2018 they reached the number of 1’287. This confirms the relevance and the emergence of the topic in the last decade. Due to governmental policies and strategies, Chinese and European academics were the most interested in the CE. As explained in section 5.5.1 and in general throughout this chapter and the previous one, CE studies rely on several theoretical influences and follow three main lines of action (Merli et al., 2018): the first targets the social and economic dynamics at macro and administrative level; the second aims to encourage firms’ participation in circular practices implementation to encourage the diffusion of new kinds of product design; the third, developed at meso-level, relates to industrial symbiosis experiences. Table 6.3 confirms that the scientific production about CE is split among different subject area/research fields. In Scopus subject area categories define the main research fields and are attributed by in-house experts to every scientific contribution in the database based on the aims and scope of the journal and the title of the contribution using the All Science Journal Classification (ASJC) (Scopus, 2020). The top three are environmental science, engineering and energy, directly followed by business, management and accounting showing an increasing interest from the managerial field for circular practices. It is then clear that different research streams come from different epistemological fields, such as ecology, biology and economics (Homrich et al., 2018). Hence, the increasing relevance of the idea of the CE as a way to achieve the general purpose of “sustainable development” encouraged scholars to come up with diverse ways to understand it through different “field-specific” interpretations. Consequently, the definition of CE is not static and it includes an extensive range of principles and proposals.

Table 6.3: Breakdown of CE papers per research field (top 10)

Subject Area	No. of publications
Environmental Science	1’911
Engineering	1’671
Energy	964
Business, Management and Accounting	806
Social Sciences	781
Economics, Econometrics and Finance	464
Computer Science	365
Materials Science	364
Chemical Engineering	318
Earth and Planetary Sciences	287

The richness of epistemologic nuances of CE leads critics to question its potential,

[3] The query was related to title, abstract and keywords. The precise syntax is TITLE-ABS-KEY (circular AND economy).

holding that it lacks of elements of conceptual clarity (Lieder et al., 2016). For that reason, the CE has been defined as *"an idea and an ideal"* by Gregson et al. (2015) while Blomsma et al. (2017) stressed that *"theoretical or paradigmatic clarity regarding the concept of CE has yet to emerge"*. Scholars and private actors showed a complete different attitude towards the phenomenon. On the one hand, scholars tried to overcome the lack of clarity through meticulous literature studies and comparisons. D'Amato et al. (2017) performed a comparative analysis of CE, green economy and bioeconomy, finding out that bioeconomy could be understood as a part of green economy, confirming the results of Kleinschmit et al. (2014). Furthermore, Homrich et al. (2018) in their study used a combined approach, using bibliometrics, semantic and content analysis, in the attempt to identify the main research streams of CE. Kirchherr et al. (2017) tried to overcome the confusion and the ambiguity about CE analysing the historical development of CE and the different value retention options (ROs) for products with an increased circularity.

On the other hand, consultancy and advocacy framed CE as a new phenomenon, envisaging a stark contrast with the previous paradigm (EMF, 2013; Haes et al., 2016), spreading this idea among firms and practitioners. Moreover, the Ellen MacArthur Foundation, aware of the complexity and versatility of the concept, tried to operationalize it through the ReSOLVE framework[4] (Ellen MacArthur Foundation, 2015a) aiming to develop a comprehensive categorization of CE practices. Thus, it can be said that CE has been associated with a wide variety of concepts during the last thirty years and this multiple affiliations might have hindered the search of both theoretical and operational clarity. Considering the large number of researches about CE, their broad spectrum of approaches and their multiple applications, a unified perspective of the keywords of CE could support its implementation and therefore enhance the adoption of sustainable practices.

6.3.2 Research design

Wikipedia: opportunities and threats

Wikipedia is a powerful tool for knowledge creation and interpretation; nowadays it is the largest and most visited encyclopedia in existence. It is densely structured and the articles proposed are rich in linkages with other articles and online pages (Milne et al., 2008). It covers a wide range of fields such as the arts, history, geography, sports, science, music and games. Therefore, Wikipedia could be seen as a "small world", where any page, on average, is separated by only 4.5 clicks (through internal links on Wikipedia pages) from any other one (Wenger, 2020). Small World is a type of random network introduced by Watts et al. (1998) in an article on Nature in 1998 based on the six degree of separation law[5] where on average each node of the network is separated by less than six links

[4]The ReSOLVE framework refers to the main pillars and strategies behind the CE like shift to renewable energy (Regenerate), share assets and reuse (Share), optimization of the efficiency of the process (Optimize), recycling and remanufacturing (Loop), or dematerialise products (Virtualise) or change business models and technologies (Exchange).

[5]The six degree of separation law, is a popular law in social science that affirms that the average distance between people is logarithmic with respect to the size of the population. Each connection between two people (e.g. two friends) represents a distance of one, thus on average 4.5 steps in a chain of friends-of-friends are

(Guare, 1990). Thus, since it is becoming a "database storing all human knowledge", Wikipedia mining is a promising approach which integrates semantic purposes with Web 2.0 (Nakayama et al., 2008). The pages of Wikipedia are created and checked regularly by expert users who create a large and reliable peer-to-peer community. Moreover, as a corpus for knowledge extraction, Wikipedia's peculiar features are not limited to its scale, but they entail a dense link structure, disambiguation based on URL, brief link texts and well structured sentences as well. The fact that these characteristics are relevant to extract accurate knowledge from Wikipedia is highlighted by a number of previous researches on Wikipedia mining, mainly focused on semantic relatedness measurements among concepts, such as Gabrilovich et al. (2007) and Ponzetto et al. (2007). However, Wikipedia does not allow the user to distinguish unambigously between synonyms, polysemy and hierarchical/hyper-hyponymy relations. In linguistic, hyponymy is a subtype of an hypernymy (e.g. red is a color), while polysemy represents the property of a word to assume multiple meanings. Let's think to the word *tree* which may have different meanings (e.g. a plant or a hierarchical tree in computer/data science). Thus, without proper algorithms or a manual check, starting a data mining process from random anchor pages may lead to errors and misleading findings. The same errors may occur exploring the Wikipedia network, i.e. following the links among the pages, when the links appear in general and confused context (Milne et al., 2008). In addition, critics often question the reliability of the content generated in Wikipedia and stress the complexity of the rules for new contributors and the presence of an "elite" of contributors enforcing these rules. Each page in Wikipedia is the product of a number of different social forces, due to corresponding people (or bots), who cause fluctuations of information, and give in every instant a visible representation for every chosen argument (Marchiori et al., 2018). The theme of "edit wars" in Wikipedia is largely treated in the literature (Borra et al., 2015; Sumi et al., 2011; Yasseri et al., 2012). An even bigger issue for this research might be that many articles in Wikipedia are just a few lines long, hence not giving complete information about the topic considered.

Methodology

This section explains the steps followed to analyse the network of words related to the CE. The methodology consists of three main steps/modules: 1) the construction of a seed list, i.e. an initial seed list of keywords related to the CE is extracted from the Scopus database and then manually parsed, 2) the Wikipedia scraper, in which the existence in Wikipedia of each keyword from the seed list is checked and expanded with all the links in each of the web pages, and three networks (a general one, a technology-related and a field-related network) are built by using a list of keywords to filter each page and label it as a field or a technology, and 3) a Social Network Analysis, where the three networks have been analyzed in terms of A) centrality degrees to highlight the most important nodes and B) clusters, by running the modularity algorithm, to identify the main field/technology groups. Figure 6.4 shows the main steps of the adopted procedure.

The first step consists in the generation of a seed list. The seed list was generated by extracting keywords from the results of a query with the words "Circular Economy"

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necessary to reach any person in the world.

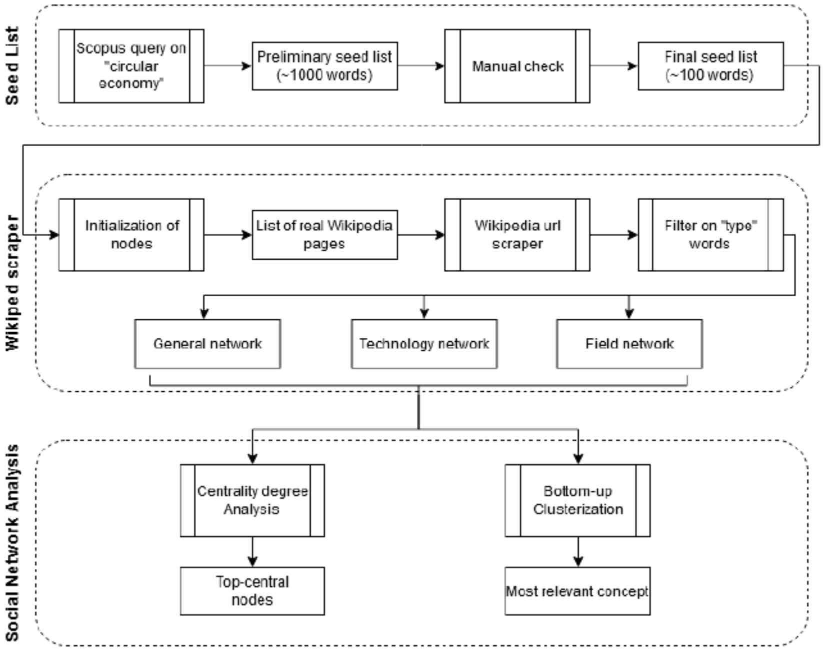


Figure 6.4: Flowchart of the adopted methodology.

in Scopus. The keywords include both those selected by the authors of the papers and those generated by Scopus itself. Then, the keywords were kept only if their occurrence was greater than 1. Afterwards, the seed list, which originally contained around 1000 words, was manually parsed, in order to choose only relevant words regarding the CE. The manual check is aimed at excluding off-topic words such as names of countries or cities (e.g. The Netherlands, China, Beijing, . . .), polysemic words (e.g. deconstruction) and general concepts (e.g. flow, experiment, crisis, analysis, ...). This process resulted in a list of more than 100 words, obtained after the parsing and cleaning process, the final seed list. Moreover, 70 words from the final seed list were labeled as enabling technologies for the CE and 50 words were labeled as fields and branches of study related to the CE. These other two sub-classifications were made to verify the validity of the two initial sub-networks with the filter based on two small dictionaries (one for the field and one for the technology). The full list of keywords is reported in the table A.1 Appendix A.1.

The second step was related to the scraping of the Wikipedia pages. The final seed list, from the first step, was adopted as input for the initialization phase represented on the left side in Figure 6.5. Figure 6.5 shows the flow of the developed scraping software (developed in R) for, on the left, the initialization phase and, on the right side, for the Wikipedia scraper and the network builder. Within the initialization phase, the initial node list for the network is created with a triple check on, first, the existence of a related Wikipedia webpage, second, the previous existence of the node and, finally, the type of the page. The

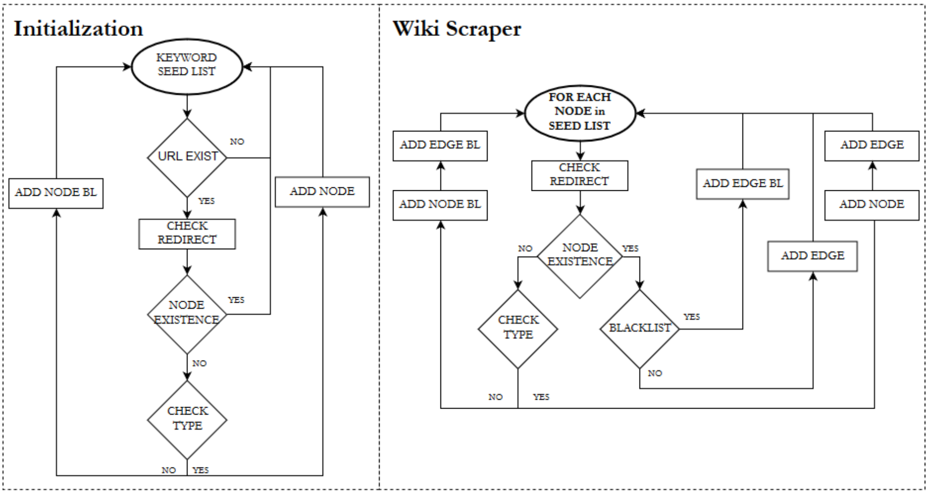


Figure 6.5: Flowchart of the Wikipedia scraper software developed in R.

first check consists in automatically building the modular Wikipedia url string such as `https://en.wikipedia.org/wiki/[FIRSTWORD]_[SECONDWORD]` and then check its existence. If a keyword consists of more than two words, it is necessary to add an underscore to separate each word. The second check is the one regarding the existence of the node, to ensure that, after a possible redirect, only a unique node exists for each page. The node existence check was performed on the url of the page. Finally, the third check consists in parsing and storing the first sentence of each Wikipedia page and check if one, or more, *type* keywords appear. The type keywords have been selected in order to label each node as relevant field or technology. 16 words related to the concept of *field* and 23 words related to *technology* were selected. The selected keywords were chosen manually in order to include each possible synonym used in Wikipedia to describe a research field or a technology, methodology or technique. The field dictionary includes keywords such as field, model, branch, framework, system, subject while the technology dictionary includes keywords as technolog, methodolog, techniqu, analys and so on. If they appear in the first sentence, then, the node was added to the node list while, if not, the node was added to a blacklist (BL). The blacklisted nodes were labelled with an ad hoc flag. Furthermore, a check on the redirect was added, in order to guarantee the uniqueness of the added nodes due to url redirection (for instance, biofuels is redirected to biofuel). After the initialization phase, the Wikipedia scraper module starts to parse all links (i.e. urls) from the seed list nodes. The Wikipedia scraper performs, at each step, the same control of the initialization phase, except for the url exist control. This is explained by the fact that when the scraping algorithm starts from an existing Wikipedia page it follows only links directed to other Wikipedia pages.

Finally, a Social Network Analysis of the three networks was performed thanks to the software Gephi (ver. 0.9.2) analysing the Betweenness centrality (Brandes, 2001), the Authority index (Kleinberg, 1999), the PageRank index (Brin et al., 1998) and identifying the clusters thanks to the Modularity, with resolution 1.0 (Blondel et al., 2008), whose algorithm implemented in Gephi looks for the nodes that are more densely linked together than to the rest of the network (Blondel et al., 2008). The intuition about centrality is that it denotes an order of importance on the vertices or edges of a graph by assigning real values to them (Brandes, 2001). Betweenness centrality of a node measures its ease to act as a bridge among any couple of nodes of the network. Indeed, the definition of Betweenness centrality is given by the expression $g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$ where σ_{st} is the total number of shortest paths from node s to node t and $\sigma_{st}(v)$ is the number of those paths which pass through v. The PageRank index defines the importance of a node in a network considering how many links it receives weighted on the PageRank score of each neighbour. It is a measure of the likelihood of reaching a certain node starting from a random node of the graph. The PageRank index has an intrinsic limitation, i.e. it does not weigh recursively the importance of the nodes which point to the selected node. This limitation is overcome by the Authority index. Authority centrality is one of the two generated by the algorithm HITS (Hyperlink-Induced Topic Search), together with Hubs. Authority, in particular, weighs the inbound link pointing to a node depending on the importance of the source node. The importance of the source node is given by the Hub index, which depends on the number of outbound links and on the importance of the target nodes. The values of the two indices are defined recursively; therefore, a higher value for Hubs takes place if the node is pointing to many nodes with a high Authority score. In that sense, a node with a high Authority score is supposed to hold useful information because it is pointed to by many nodes with a high Hub score.

6.3.3 Results and Discussion

The results include 3 networks and the related identified dictionaries: the first one (Figure 6.6) is generated using the seed list identified above, without filters; the second one (Figure 6.7a) points out the technologies related to CE, while the third graph (Figure 6.7b) shows the branches and the fields of study related to CE. The two sub-networks, i.e. the technology and the field ones, were obtained by selecting only the Wikipedia pages which contain in the first sentence one, or more, of the words representing the *type* keywords as described previously. The dictionaries generated can be represented with a graph in which each node represents a word and each edge represents a link of Wikipedia. In addition, these networks have been used to generate metrics, such as Betweenness, PageRank and Authority, which could be used to generate useful indicators in future researches. In each of the subsequent figures, the nodes with a degree lower than 5 are dropped out, the dimension of the label reflects the Betweenness index while the dimension of the node reflects the degree of the node (inbound plus outbound links). The colours represent the node labelling obtained through the Modularity algorithm (Blondel et al., 2008). Table 6.4 summarizes the global network parameters for each graph. The average degree, the modularity, the network diameter and the graph density are reported. The average degree is simply the average number of edges/links per node considering all the nodes of the whole network, while modularity measures the validity, and its strength, of a particular partition of a network into groups (i.e. modules). More precisely, the modularity lies in the range $[-1/2, 1]$ (Brandes et al., 2008), where a positive high number represents a network with a high density of edges/links in the same group and a low density among different groups/modules. It is computed as the fraction of links per node within the same group minus the expected likelihood for an equivalent random graph (in terms of degree distribution). In other words, it represents the strength of a partition of the network, assessing the density of connections within the same module. The network diameter and the graph density are other two measures that reflect a global property of the network. The network diameter is the longest of the shortest paths among all the nodes. The shortest path represents the minimum distance between two nodes. Thus the network diameter represents the longest minimum distance among all the pairs of nodes of the network. Finally, the graph density is simply the fraction of the existing links/edges over the total possible number of links in a fully connected network, i.e. when all the nodes are connected with all the other ones. As shown in table 6.4, the overall network is the least dense graph but it has the highest average degree. The most dense graph is the technology graph while the field one is the network with the lowest average degree.

Table 6.4: CE overall network measures

Graph name	Average degree	Modularity	Network diameter	Graph Density
All	12.75	0.351	5	0.021
Tech	8.83	0.294	5	0.55
Field	6.34	0.278	5	0.047

Bottom-up clusters

The first graph (Figure 6.6) shows the network of words generated from the seed list without using any filter in Wikipedia. This provides an overall image of the main concepts related to the CE. The modularity algorithm (Blondel et al., 2008) identifies 6 main clusters, represented by the different colours in Figure 6.6. Light green represents the cluster related to sustainability, sustainable development (SD), environmental economics and ecology. It aggregates previous broad and general disciplines related to the environment. The orange cluster aggregates the circular economy, life-cycle assessment (LCA), material flow analysis (MFA). The blue one is related to waste management and extended producer responsibility (EPR). The purple cluster shows a focus on water reuse, anaerobic digestion and waste water. The red cluster is focused on bioenergy, biofuels, biogas and bioeconomy. Finally, between the purple and the red one a small yellow cluster represents the waste electrical and electronic equipment (WEEE), the rare-earth elements (REE) and other metals. Thus, we labelled the six identified clusters as: 1) Sustainability, 2) Material Flow Analysis, 3) Waste Management, 4) Water Management, 5) Waste Electrical and Electronic Equipment and 6) Bioeconomy.

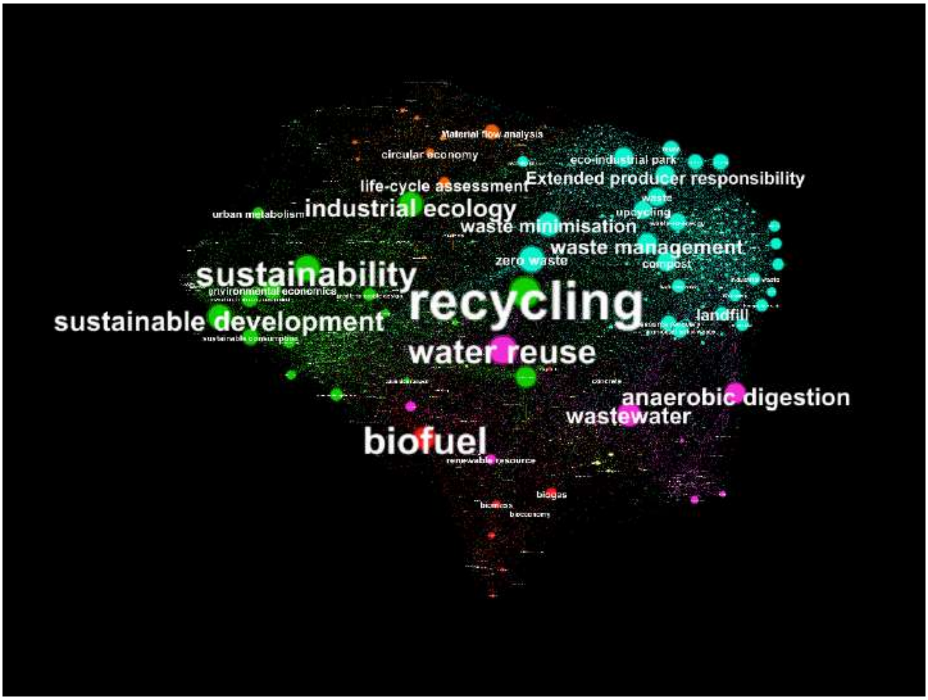
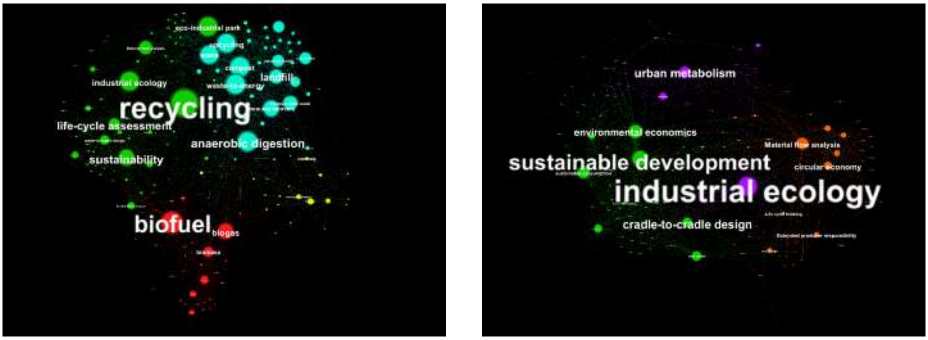


Figure 6.6: CE overall network.



(a) Technology (b) Field

Figure 6.7: Technologies and field sub-networks.

Figure 6.7a exhibits the most relevant technologies related to the circular economy, while Figure 6.7b shows the related fields. From the technology network four of the six clusters described in the overall network can be recognized. The Sustainability cluster (the green one), the Waste Management cluster (the blue one), the WEEE cluster (the yellow one) and the Bioeconomy cluster (the red one). The orange and the purple ones were in part absorbed and aggregated to the other clusters and in part they are not considered because of the type filter. Finally, Figure 6.7b shows the related fields. Two of the six clusters can be identified: the Sustainability cluster (the green one) and the Material Flow Analysis cluster (the orange one). The violet cluster, instead, is a mix of fields from different clusters of Figure 6.6 and it aggregates keywords such as urban metabolism, industrial ecology and ecology.

Centrality degrees

Table 6.5, 6.6 and 6.7 show the top five nodes with respect to three centrality indices: Betweenness, the PageRank and the Authority, respectively. Betweenness centrality analysis shows that fundamental nodes for the CE are recycling, biofuel and sustainability. This is not at all a surprising result, because the idea of recycling is strongly linked to the CE concept through the 3R imperative "reduce, reuse and recycle". Indeed, this paradigm was already existent and mentioned in several papers about industrial ecology, reverse logistics and closed-loop supply chain management. Furthermore, Murray et al. (2017) underline that the urge for Recycling started many years before the upsurge of CE, encouraged by consistent policy interventions in different countries, such as *basic law for establishing a sound material-cycle society* in Japan and *the waste avoidance and management act* in Germany, both enacted in 2002. This entails that the field of CE could not be originally and directly associated with the 3R paradigm, including therefore the practice of recycling (Kirchherr et al., 2017). Biofuel, a fundamental keyword for the dictionary of CE, dates back to the Seventies and it experienced a steady growth since then (Lapan et al., 2012). Comprehensive bibliometric reviews about CE (Geissdoerfer et al., 2017; Kalmykova et al., 2018; Kirchherr et al., 2017) do not mention biofuel at all. Moreover, D'Amato et al. (2017) argue biofuel is a concept related to the idea of bioeconomy but not associated with green and circular economy. In that sense, even if it exhibits a high Betweenness, Biofuel seems an older topic than CE itself, whose importance has been growing over the last decade driven by governmental policies more than by the emergence of the idea of CE (Sorda et al., 2010). The concept of sustainability has its roots in the idea of sustainable development(Brundtland et al., 1987) and it seems more "open ended" than the concept of CE (Yuan et al., 2006). Sustainability as a topic is experiencing a clear growth trend, considering the query of sustainability in Scopus generates 9'142 results for 2010 and 22'250 in 2018, with an increase of 143 %. The upwards trend is real but lower than the one of CE. In addition, recycling and sustainability were included among the most important words for number of occurrences in selected articles about CE in Geissdoerfer et al. (2017), confirming the validity of the methodology developed in this paper. For what concerns the main keywords for the fields related to CE, it is no surprise to find industrial ecology with the highest value of Betweenness (0.036), because, as stated previously, CE emerged as a separate field from industrial ecology itself. On the other hand, cradle-to-cradle design occupies the 4th position for Betweenness and this is an interesting result because, as argued by Kirchherr et al. (2017), CE only very recently started to be associated with this idea. The result obtained could then entail that CE might be pushing towards the emergence of cradle-to-cradle, linking it to other fields of expertise. The CE technology network demonstrates again the centrality of recycling and biofuel, but giving more importance to the key processes and technologies for CE. Anaerobic digestion (third position in terms of Betweenness in the network) is a fermentation process where organic raw materials such as food waste, sewage sludge and other industrial wastes are converted into biogas (Holm-Nielsen et al., 2009). Due to its close connection with waste, from a cluster point of view, anaerobic digestion is closer to the "waste" cluster. According to Fagerström et al. (2019), the process of anaerobic digestion is directly linked to the production of biogas, therefore to the concept of bioeconomy. In addition, in their report the authors demonstrate that anaerobic digestion and the production of biogas is closely related to CE through four case studies. To sum up, the most influencial nodes of the three networks, defined by Betweenness index, might not be considered per se as elements of novelty directly associated to the idea of CE. On the other hand, the presence of concepts such as C2C, for instance, might be a sign of cross-fertilization among diverse concepts, glued and enhanced by the growing paradigm of CE.

Table 6.5: Betweenness, top 5

	All		**Field**		**Tech**	
Rank	Keyword	Value	Keyword	Value	Keyword	Value
1	Recycling	0.014	Industrial Ecology	0.036	Recycling	0.460
2	Biofuel	0.011	Sustainable Development	0.025	Biofuel	0.358
3	Sustainability	0.009	Urban metabolism	0.013	Anaerobic Digestion	0.018
4	Water reuse	0.009	Cradle-to-cradle design	0.013	Sustainability	0.017
5	Sustainable Development	0.007	Environmental economics	0.011	Life-cycle assessment	0.016

The PageRank top values are consistent with the Betweenness centrality ones. Recycling occupies again the first position in the overall network and in the technology one. Other important words detected by the PageRank algorithm are sustainability, biofuel and LCA, already identified by Betweenness. On the other hand, permaculture, first ranked by the PageRank algorithm for the field is an interesting finding. The goal of permaculture is deeply rooted on biomimicry school of thought; it aims to manage the urbanized ecosystem allowing the satisfaction of population's needs, while preserving the stability of natural ecosystem (Rhodes, 2015). Permaculture could then be defined as a mixture of fields, such as architecture, biology, silviculture and zootechnics. The captivating fact about permaculture is that it seems to have a different nuance compared to sustainability: permaculture has a *"value-added factor which extends beyond what might be merely maintained or sustained"* (Rhodes, 2015). Thus, while sustainability aims to maintain what already exists, permaculture's purpose is to be regenerative. For instance, a regenerative product must not only be 100% recycled but it also has to improve environmental conditions at any stage of its production and use. Since there is no waste in nature, this idea of regeneration seems to upgrade the concept of Sustainability towards a real circular economy.

The highest values for the Authority scores are linked to the idea of waste (waste management, waste hierarchy, waste minimization etc). This result emerged from the structure of the analysed network and it can be noticed, in a qualitative way, by observing the densities of links and the number of high degree nodes of the Waste Management cluster in Figure 6.6. Waste has been the very first topic faced, in the 90s, by the CE but

Table 6.6: PageRank, top 5

	All		Field		Tech	
Rank	Keyword	Value	Keyword	Value	Keyword	Value
1	Recycling	0.003	Permaculture	0.013	Recycling	0.0102
2	Regenerative Design	0.0028	Regenerative Design	0.012	Biofuel	0.0095
3	Greenhouse gases	0.0024	Cradle-to-cradle design	0.010	Life-cycle assessment	0.0093
4	Circular Economy	0.0024	Sustainable Development	0.0099	Sustainability	0.0088
5	Sustainability	0.0024	Infrastructure	0.0096	Efficient energy use	0.0087

the interest for waste management started in the 70s, confirmed by a steep increase of the topic in the literature of industrial ecology and cleaner production.

Table 6.7: Authority, top 5

	All		Field		Tech	
Rank	Keyword	Value	Keyword	Value	Keyword	Value
1	Waste Management	0.109	Sustainable Development	0.161	Recycling	0.165
2	Recycling	0.104	Rebound Effect	0.150	Waste hierarchy	0.163
3	Waste hierarchy	0.099	Industrial Ecology	0.147	Heat waste	0.158
4	Sewage treatment	0.099	Anthropogenic	0.143	Downcycling	0.157
5	Waste Minimization	0.098	Natural Resource	0.143	Scrap	0.154

6.3.4 Limitations and further research

This work shows a novel methodology based on social network analysis and quantitative text analysis able to easily extract, identify and analyse relevant keywords, technologies and sub-fields related to a particular research field/branch (in our case the CE). Starting from the work of Chiarello et al. (2018), the proposed methodology introduces a simple way to assess the importance of keywords and concepts based on the Wikiepdia network by giving to each concept (i.e. a Wikipedia page) a precise score based on the centrality degrees and, consequently, by evaluating its importance. Moreover thanks to the quantitative text analysis, it is possible to classify each page according to precise criteria (in our case fields and technology) simply by analysing the text of each page. In other words, the main potentiality of this methodology lies on the analysis of Wikipedia, which, currently, is the greatest and most accurate encyclopedia in the world. The modular layout of each page allows easily to extract information thanks to a data scraping algorithm and a simple bot. Moreover, the "small world" structure permits to easily explore the whole network. In this work, the social network analysis, supported by a text analysis, has been proven to be an excellent approach to identify and extract relevant concepts related to the CE. The same approach can be easily generalized to other fields such as artificial intelligence, industry 4.0, sustainable development goals, green chemistry and so on.

This research work is a first step towards the creation of a robust, systematic and scalable methodology for network analysis using Wikipedia. Nevertheless, further improvements need to be implemented: in the first place, the seed list creation process has to be empowered in order to obtain an automatic and reproducible method, that could then be applied to a diverse set of research fields. The manual nature of this activity deeply influenced this work's results. Indeed, despite its potentiality, this methodology revealed several limitations which must be further investigated. The obtained final networks, i.e. the field and the technology ones, are strongly affected by the choices made during the selection of the final seed list of keywords, and are sensitive to parameters, such as the degree filter, the modularity resolution or the definition of the field and technology dictionaries. When varying anyone of these setting parameters, the final results are considerably affected.

More in particular, we first noted that considering the final seed list of keywords, a more general algorithmic approach has to be developed. Indeed, almost all the most important and crucial nodes revealed by the social network analysis belong to the initial seed list because the graph analysed corresponds to the nearest neighbourhood of the initial list. A possible solution could reside in improving the seed list creation process, aiming at an automatic expert-independent approach, providing a reproducible methodology; this goal might be obtained by filtering the initial keywords list retrieved from Scopus by a pre-fixed occurrence threshold or by fixing a criterium in the paper selection activity in first place (i.e. filtering by top-cited papers).

Second, the "type" dictionaries used to "filter" the fields or the technologies strongly affect the final graph. Adding, or removing, a single word might lead to a completely unpredictable result. Although the type keyword approach used in this work is a great starting point towards the automatization of the dictionary creation process, it needs to be refined.

Third, the degree filter also has a noteworthy effect on the final graph. Without the degree filter, i.e. considering also nodes with only one link, a higher number of clusters were obtained but the centrality indices were strongly affected by hundreds of nodes with no importance at all for the circular economy. Thus, the choice of filter nodes with a degree lower than five was necessary to drop out not strongly interconnected nodes in order to minimize biases in subsequent analyses of centrality degrees due to off topic nodes. In addition, the degree filter allows to minimize biases due to the total number of links of a Wikipedia page, which is not an interesting information and it can strongly affect centrality results simply because of some Wikipedia pages can have more than one thousand links to other pages. On the contrary, analysing the network without the degree filter allowed to identified more precise and bounded clusters with respect to the discussed networks. This aspect can be partially overcome by varying the resolution parameter of the modularity. Indeed, values lower than one allow to identify smaller communities.

Finally, the networks obtained from Wikipedia are user-generated and some research fields or knowledge might not appear at all or they might be under-evaluated. Newest, most innovative and recent research fields may be under-represented or may be penalized by the directionality of links, if the directed network is considered. For instance, a newer field cites an older one, e.g. circular economy points to biomimicry, but not viceversa.

Future studies and investigations are necessary to solve some of the discussed limitations. For instance, to explore deeper the Wikipedia network, stronger and more powerful type dictionaries are necessary in order to avoid the polynomial explosion of the number of nodes and edges. Indeed, the number of nodes increases by, at least, two orders of magnitude since each page has one hundred links on average and some Wikipedia pages can have more than one thousand links. It is trivial to show that at each step of the Wikipedia scraper algorithm, i.e. nearest neighbours, 2nd order neighbourhood, the number of nodes increases according to the following rule $n_{t+1} \sim n_t^2$, where n_{t+1} is the number of nodes at the step t+1 and n_t at step t. In order to avoid this explosion, a blacklist or a stop list of keywords can be implemented. On the contrary, to contain the network explosion, only pages which contain certain crucial keywords can be considered. For instance, considering this work, pages which do not contain words such as Sustainability, waste, environment, or which do not contain couple or triplet of words, could be excluded. Otherwise, a ranking system, based on keywords, can be implemented by assigning a score to each page and selecting only pages with a score greater than a determined thresholds. Score, for instance, can be based on machine learning algorithms which assign to each word a weight. Furthermore a topic modeling analysis on single pages can be implemented in order to compute the "distance" between pages and the initial seed list or the nearest neighbours in order to drop out too far away Wikipedia pages. Otherwise, an algorithm based on the network can be developed in order to exclude nodes, or entire branches, which do not connect with the initial seed list after two or more steps. Finally, further analyses and considerations could be done by comparing the clusters obtained implementing the methodology presented in this work (bottom-up) and the clusters that would be expected (top-down). In addition, it would also be of great interest, once the above-mentioned improvements have been applied and a more accurate technology dictionary with reference to the CE has been created, performing a crossover with Industry 4.0, Artificial Intelligence, Sustainable Development and so on.

6.3.5 Concluding remarks

The presented methodology shows how Wikipedia can be used as a "small world" and allows to analyse, in detail, a precise field extracting useful information for researchers, practitioners and policy-makers. Six main clusters emerged: 1) Sustainability, 2) Material Flow Analysis, 3) Waste Management, 4) Water Management, 5) WEEE, 6) Bioeconomy. The most crucial nodes are Wikipedia pages such as recycling, biofuel, anaerobic digestion, sustainability, industrial ecology or water reuse.

In conclusion, is the CE a new paradigm or is it a relabeling of existing knowledge? From the analysis of the obtained graphs CE appears to be a quite important node and it has a dedicated cluster, with existing fields such as material flow analysis and life-cycle assessment, for instance, but it does not seems to connect far-away fields or to open a new emerging branch. Moreover, despite having its own cluster, Betweenness centrality demonstrated that the most influencial keywords, such as recycling, biofuel and sustainability, at the present time, were not originally conceived within the framework of the CE.

On the contrary, analysing the field network, industrial ecology, sustainable development as well as urban metabolism have an important role in terms of Betweenness.

Urban metabolism and industrial ecology seem to belong to a new cluster of fields connecting, on one side, the CE cluster and, on the other side, the Sustainability cluster. The presence in the network of fields only recently associated with CE, such as C2C, might be interpreted as an interesting signal of cross-fertilization promoted by the CE paradigm. The emergence of permaculture as first-ranked result by the Pagerank algorithm could be interpreted as a further sign of this process.

Table 6.8: Main schools of thought and inherited concepts for CE.

Field	**Underlying idea & potential CE-inherited concepts**
Schools of thought (as recognized by EMF)	
1. Industrial Ecology	A. Waste management & symbiosis among processes
2. Cradle to cradle	A. Eco-effectiveness B. Technical & Biological flows C. Waste management
3. Biomimicry	A. Philosophical framework B. Nature as a model, measure, and mentor
4. Performance Economy	A. Change in ownership B. Product-as-a-service
5. Blue Economy	A. Business model innovation
6. Regenerative Design	A. Reference system for the environment B. Minimum impact to regenerate ecosystems
Other concepts and fields	
7. Extended Producer Responsibility	A. Change in ownership
8. Sustainable Development	A. Needs for future generations B. Time dimension
9. Environmental Economics	A. Economy-environment interactions B. Existence theorem
10. Green Economy	A. Green technologies B. Renewable energy
11. Life Cycle Thinking	A. Thinking in system B. Environmental impact assessment
12. Eco-design	A. Function of objects B. Toxicity of materials C. Design for disassembly
13. Physical sciences	A. Planetary boundaries B. Biogeochemcal cycles
14. Psychology	A. Psychological & physiological needs
15. Human Ecology	A. Population dynamics
16. Resilience	A. Dynamic Equilibrium of ecosystem

6.4 Conclusion

So, how could the circular economy be considered? In section 5.5, I have asked a few relevant questions to frame the CE. *How is the circular economy defined?*, *what does it* *characterize the circular economy?*, *What are the main features and set of rules for a circular economy?*, *What are the main differences between the circular economy and previous knowledge fields?*.

In my opinion, the CE, in the current state of art, can be classified neither as a new paradigm nor simply a relabeling, or rebranding, of past knowledge. Following the transformationist school of thought, as described by Reike et al. (2018), the CE should embrace the three sustainability pillars with a systemic approach but, currently, it is still far from being considered a new paradigm, since all relevant underlying concepts are far from new. According to Blomsma et al. (2017) the circular economy may be defined as *"an umbrella concept"*. An umbrella concept as stated by P. Hirsch et al. (1999) is *"a broad concept or idea used loosely to encompass and account for a set of diverse phenomena"*. Considering the CE an umbrella concept is in line with CIRAIG (2015) that stated *"circular economy is a multi-level, socio-constructed concept that can either be considered a paradigm shift, a new toolbox, a conceptual umbrella or a portmanteau discipline*.

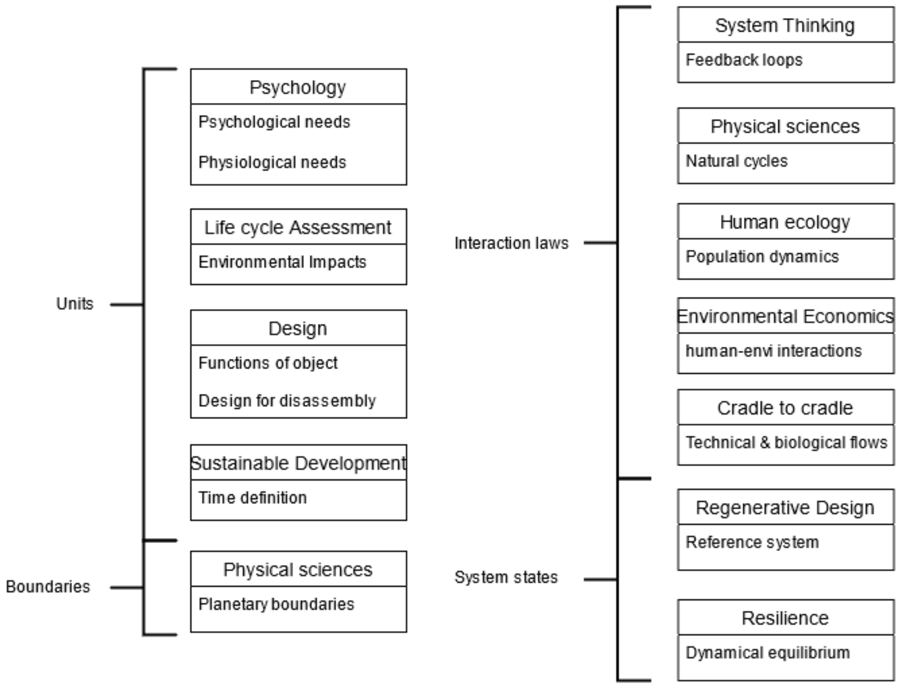
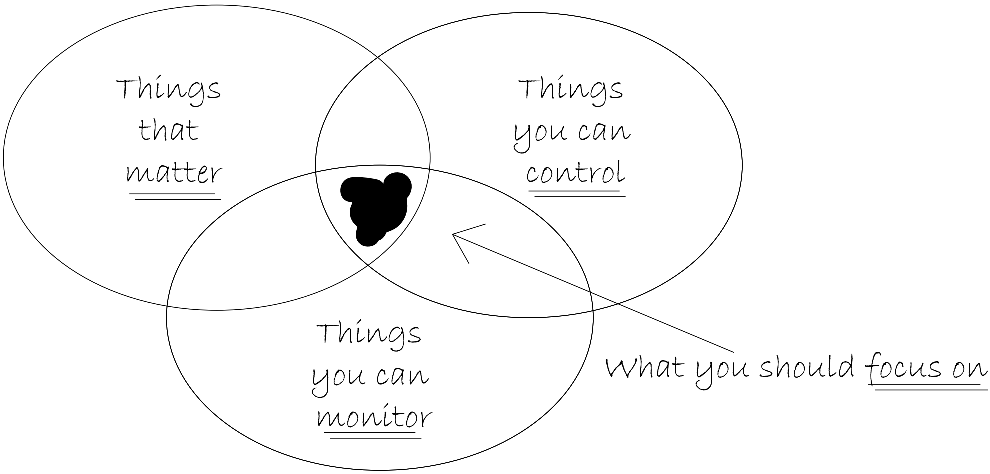


Figure 6.8: CE underlying concepts and ISDT principles. Simplified representation of basic previous concepts and as they interrelated with the four principles (units, boundaries, interaction laws, system states) of ISDT of Dubin, as described in Gregor et al. (2007).

In this respect, defining the CE as an umbrella needs some final clarifications. Following previous definitions, the CE should include, or at least refer to, previous knowledge and schools of thought and it should inherit some concepts, methodologies and approaches from each one of them. As far as it was possible, I summarized in tab. 6.8 the main discussed fields and schools of thought and their underlying concepts, as they are (they could be) be inherited by the CE. We have seen, some concepts are rather pragmatic (e.g. waste management, renewable energy, circular business model) and may stimulate a positive change for businesses, public institutions and/or citizens, while some others are theoretical and philosophical (Nature as a model, existence theorem, function of objects). In this sense, the CE may be intended as an umbrella, if and only if it will include previous fundamental concepts, as the time dimension (inherited from the sustainable development definition and from environmental economics), the planetary boundaries (strictly connected to the idea of not to affect future generations), as well as interactions rules among different levels (e.g. thinking in systems). On the contrary, following the discussion about the Information System Design Theory (Gregor et al., 2007), in order to define the CE as a new paradigm or theory, it is necessary to identify (in this first phase) the basic *"units"*, *"boundaries"* and *"interaction laws"*. Figure 6.8 summarizes the identified concepts and preliminary maps them into the three first principles of ISDT, according to Gregor et al. (2007).

At this point, once understood what circular economy should, or could be, the next step is to look deeper into existing methodologies, approaches, and tools which allow to properly measure the environmental impacts or the circularity of human and natural activities, since, again according to ISDT, the following principles to define a new theory are *testable propositions*, *principles of implementations*, and an *expository instantiation*.



7. How to assess circularity

The need for evaluating, assessing and monitoring environmental impacts of human activities has been largely discussed in the previous chapters. Currently, there exist several different techniques, tools, methodologies and approaches to measure the environmental impacts of a particular product or process. The approach one should adopt depends on the goals and scope of the study, as well as on the level, scale and boundaries. For micro level assessment, i.e. at the level of product/process, the most proper methodologies generally are the Life Cycle Assessment (to evaluate precise environmental impacts), the eco-design and design for disassembly criteria (to assess the recovering potential of materials and components of a particular product), and the novel circularity indicators (to measure the material flows during the production, use, and EoL of a particular product/process). At meso (supply chain, organization or regional) and macro (national and international) scale other methodologies and tools should be preferred, as the input-output tables, system dynamics or material flow analysis, although Life Cycle Assessment or properly designed meso or macro circularity indicators also exist.

To have a complete overview and achieve meaningful findings, the entire life cycle of a product or process should be considered, from cradle-to-cradle, considering all the life phases, i.e. extraction, production, use, and the End of Life. How to evaluate the recovering potential and the closed loops, such as repairing, reusing, remanufacturing products, just to name a few, it is still under debate and no standard approach exists. Some researchers attribute the impact of recycling to the original product, other to an eventual new produced product, while other split the impacts to both. Such complexity in the environmental evaluation has been addressed by different national and international standards. Indeed, to conduct an environmental, or a circularity, assessment, first of all it is crucial to have an overview on current national or global Standards. Standards are guidelines provided by national or international companies - e.g. the International Standardization Organization (ISO) - in order to allow and facilitate the comparison among different studies. National certification systems (BS, British Standard, or UNI, Italian National Unification Body), European certification systems (CEN, European Committee for Standardization) or worldwide certification systems (ISO, International Organization for Standardization) are therefore part of any new context in which the proliferation of approaches, methodologies and definitions makes it difficult to compare economic, environmental and/or social analyses, and aim to simplify procedures by standardizing existing ones to be followed in certain fields. Focus 7.1 briefly introduces the existing standards for the circular economy in order to introduce the detailed discussion in the next sections.

Focus 7.1 — Standards. Currently there is not yet a global standard to assess the circularity of products or services - although it is under debate - but there exist a few national standards and recognized certificates.

Historically, environmental impact analysis can be divided into two different approaches, i.e. a relative and an absolute one. Relative approaches include, for example, the so-called cost-benefit analysis (CBA) which considers pollution and externalities generated by a given process as a "compensable" cost. Absolute approaches, on the contrary, aim to set a standard, constraints and precise rules regarding the exploitation of the environment (Pearce et al., 1990).

In this sense, the ISO 14040 "Principles and framework" and the ISO 14044 "Requirements and guidelines" (ISO, 2006a; ISO, 2006b) - i.e. the worldwide standards that define the minimum mandatory procedures for the assessment of environmental impacts through the use of Life Cycle Assessment (LCA) - may be considered as a *relative* environmental assessment because they do not set strict regulations for the generated impacts. The Life Cycle Assessment, in particular, consists in the quantitative assessment of the environmental impacts of a product/service considering the various life stages (from extraction to disposal). See section 7.1 for more details about LCA. On the contrary, eco-design aims to set minimum standards (e.g. toxic materials not to be used, energy efficiency of a household appliance) to be met. For further detail on eco-design principles see section 7.3.

The first real certification of circularity was introduced by McDonough and Braungart who founded the "Cradle to Cradle Products Innovation Institute" which issues the "Cradle to Cradle Certified Product Standard" globally for products that meet certain characteristics. The Cradle to cradle standard assesses aspects from the environmental impacts (Material Health, Material Reutilization, Renewable Energy and Carbon Management, Water Stewardship) up to the social equity (Social Fairness). See section 6.2.1 for further details. At national level the only circularity standards in the EU are the BS8001:2017 (British Standard) "Framework for implementing the principles of the circular economy in organizations - Guide" (BSI, 2017) and the XP X 30-901 (a standard proposed by the French standards body AFNOR) "Circular economy - Circular economy project management system - Requirements and guidelines" (AFNOR, 2018). The two certifications have significantly different structure and objectives. The XP X30-901 makes it possible to assess the circularity of projects of various kinds (from the development of business strategies to the provision of new services, product design or the implementation of new policies) and is applicable to organizations of all sizes and types promoting the use of the LCA methodology to conduct precise assessment. On the contrary, The BS8001:2017 does not provide specific requirements to be met but simply aims to be a support tool for those companies that wish to make the transition from a linear to a circular economy. It consists in a qualitative assessment (through a self-assessment procedure by answering to the dozens of questions provided) with respect to six main areas: system thinking, stewardship, transparency, collaboration, innovation, value optimization. Therefore, the English standard focuses mainly on stimulating companies to "map the production system using systems thinking tools and techniques" without indicating precise tools to use.

To date, there is no global standard or a formally recognized European standard, although in September 2018, the ISO/TC 323 (ISO, 2020) technical committee was formalized including 81 countries around the world (70 voting, 11 observers), 11 internal technical bodies of the ISO and 6 external organizations. The committee, led directly by AFNOR, the French standardization body, is divided into 4 working groups [a] for the development of four standards - i.e. ISO/WD 59004, ISO/WD 59010, ISO/WD 59020, and ISO/CD TR 59031) that will be released no earlier than 2023. At the same time, at the Italian level, a Technical Commission has been created to introduce the UNI CT 057 standard which will represent the implementation of ISO/TC 323 in Italy (ICESP, 2020b). ■

[a] 1) Framework, principles, terminology and mangement system standard, 2) Guidance for implementation and sectoral applications, 3) Measuring circularity, and 4) Specific issues of circular economy

In the rest of this chapter, the main and most relevant existing approaches and methodologies will be briefly introduced and described. In section 7.1, the basic notions of Life Cycle Assessment are presented and a few Multi Criteria Decision Analysis examples are discussed, while in section 7.2 the input-output tables are introduced which generally are used for economic and environmental analysis at meso/macro scales or to extend the boundaries of LCA studies to national and international levels. In section 7.3 and 7.4, instead, a micro point of view, i.e. the design of products, is taken into account and several product design criteria, from eco-design to design for disassembly principles, are described. A focus on the novel circularity indicators, which include both material flow analysis and design criteria, is reported in section 7.5. Finally, in section 7.6 and 7.7 the "time" aspect is targeted more in depth by introducing some approaches for recursive assessment (e.g. break-even point assessment for reuse) and the most promising technique, i.e. the system dynamics (SD). SD allows to take into account feedback loops and causalities in the circular assessment, which seems to be underevaluated in current circular economy.

The text of the next sections is partly based on and adapted from the paper "Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects" (Dario Cottafava and Ritzen, 2021), the report *Benchmarking on circularity and its potentials on the demo sites* (Dario Cottafava, Ritzen, and Oorschot, 2020), and the article "Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups" (Dario Cottafava, Costamagna, et al., 2021).

7.1 Life Cycle Assessment

Life cycle assessment (LCA) is a methodology generally adopted to quantitatively assess the environmental impacts of products, or services, life cycle (Costamagna, 2021). LCA is the evaluation process of all inputs, outputs and consequently environmental impacts of a system - a product or a service system - during its whole life cycle. The current LCA framework is globally standardized through a series of standards of the International Organization for Standardization (ISO). The ISO 14040 - *"Principles and framework"* - (ISO, 2006a) and the ISO 14044 - *"Requirements and guidelines"* - (ISO, 2006b) define the global standard.

7.1.1 Background

The idea to evaluate the entire life cycle of a product/service emerged in the Fifties in the United States (Huppes et al., 2012) within a technical report written by Novick (1959) in relation to the cost and not to the environmental impacts. Originally mentioned as *Life Cycle Analysis*, the basic concept was that a cost analysis should focus not only on the direct costs such as purchasing, transportation and wage costs, to name a few, but should also include research & development (R&D) costs, as well as the end-of-life process. Consequently, in the Seventies and in the Eighties with the emergence of environmental economics and science, LCA evolved from the original cost analysis, first, to a waste and energy analysis (R. G. Hunt et al., 1996) and, then, to the current environmental LCA. The broader environmental analyses were introduced in the Eighties by Winsemius (1990) at the Department of Environmental Management in the Netherlands to evaluate public policies. Finally, in the Nineties Life Cycle Analysis was worldwide adopted and standardized (Klöpffer, 2006) by the introduction of the ISO 14040. According to Guinée et al. (2011) the evolution of the Life Cycle Assessment followed four main periods:

1. 1970-1990: the *Decades of Conception* when the main concept behind the LCA emerged from the initial cost analysis (Novick, 1959; Sherif et al., 1981) and it evolved up to the current idea of environmental analysis (R. G. Hunt, 1974);
2. 1990-2000: the *Decade of Standardization*. In this decade, researchers began to intensively adopt LCA as a research tool in environmental studies. On the contrary, large organizations' efforts - the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) - converged to the current ISO standards (Guinée et al., 2011) and it has been adopted as a policy tool, mainly for packaging standards (EP, 1994) ;

3. 2000-2010: the *Decade of Elaboration* is the period when the LCA has been adopted worldwide by researchers as well as practitioners thanks to the ISO standards (ISO, 2006a; ISO, 2006b) and the current main database and software have been created to simplify the adoption by including dozens of impact categories. Meanwhile, LCA spread as a policy tool and the European Platform on Life Cycle Assessment (EPLCA) (European Parliament, 2020) was set up to widely adopt LCA for public policies in the European Union. In the same period, several approaches emerged to improve LCA practices, such as the environmental input-output based LCA (EIO-LCA) (Hendrickson et al., 2006), the hybrid-LCA (Suh et al., 2004), as well as different allocation methods (Finnveden et al., 2009)
4. 2010-2020: the *Decade of Life Cycle Sustainability Analysis* has been finally the decade of widening the LCA framework to both economic and social aspects by the introduction of the Life Cycle Sustainability Analysis (LCSA) (M. Finkbeiner et al., 2010) and by broadening its applications on a wider scale from the micro-level of product assessment, through the meso-scale of supply chains and organizations up to a macro-level of nation-wide LCA (Guinée et al., 2011). The most recent improvements are shown in Figure 7.1

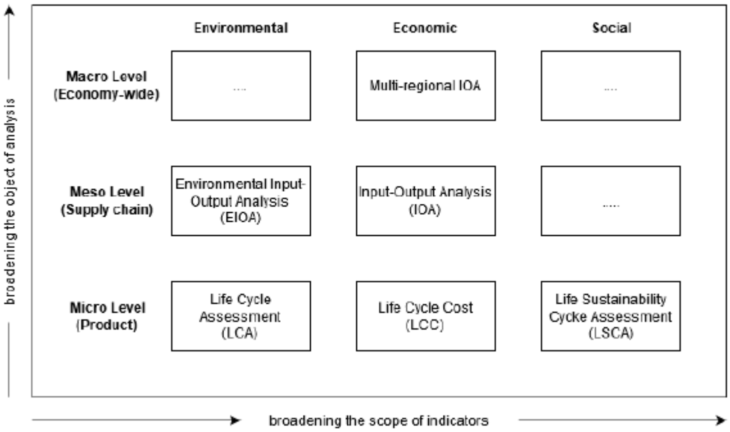


Figure 7.1: Life Cycle Assessment evolution. Adapted from Heijungs et al. (2012)

Micro and macro level LCA

Despite its original broad aim focused on public policies, nowadays LCA is widely used as a methodology for micro-assessment of products and services by practitioners and academics. An open debate, indeed, is related to its application and main focus. For instance, if assuming that cycling is environmentally better than driving a car, the same cannot be true if a broader point of view is considered. Indeed, if the money saved by choosing a bicycle instead of a car to move within a city, then is spent to buy several flights during summer or winter holiday, the environmental benefit (in terms of CO_2 emissions) is lost. Thus, a more general application for LCA focused on public policy is fundamental (Huppes et al., 2012). Simply focusing on the environmental impacts assessment of a single product or system could be not the proper approach. For instance, Thomassen et al. (2008) recommended to both conduct an attributional LCA (ALCA) and a consequential LCA (CLCA). ALCA, i.e. the most common LCA approach, focuses on the environmental impacts, in terms of the delivery of a specified functional unit, for a chosen system. CLCA, instead, evaluates the environmental impacts consequent to a variation in the functional unit due to a more general change in system. For a macro-level LCA, i.e. for policy analysis, in any case an ex-ante, or an ex-post, analysis is required in order to evaluate different scenarios and consequences of a policy instrument taking into account *"how the world would have been different"* (Huppes et al., 2012). For instance, in case of rebound effect, an attributional LCA doesn't point out the right result. For this purpose, a possible proper choice should be to conduct the so-called Input-Output LCA (IO-LCA) by extending the analysis through the use of the Input-Output models (W. Leontief, 1986) in order to intercept both costs and environmental impacts at the level of society/entire nation (see section 7.2 for further details). With the same rationale, recently the ISO/TS 14072:2014 (International Organization for Standardization, 2014) introduced the novel Organizational LCA (OLCA) (Martínez-Blanco et al., 2015). OLCA expands the assessment of the environmental impacts from the micro-level (product/service) to the level of a large organization. Thus, comparing traditional LCA with OLCA allows to identify if a change in a single process create environmental benefit both at the micro-level and at the meso-level of the whole organization.

7.1.2 LCA fundamentals

According to the ISO 14040 and 14044 standards (ISO, 2006a), a process-based LCA follows four stages as shown in Figure 7.2:

- Goal and scope;
- Inventory analysis;
- Impact Assessment;
- Interpretation.

Typically, the four stages are consequential but, as depicted in Fig. 7.2, an LCA analysis is a trial-and-error process; thus, goal and scope, inventory analysis and impact assessment phases can be tuned based on the interpretation of results in an iterative way.

Goal and scope

During the goal and scope phase no results or input/output data are collected or quantified. There is no unique definition from the ISO for this phase, but the main aim is to clearly declare the rationale and the reason of the study in an unambiguous way (Heijungs et al., 2012). During this phase, the application, the reason, as well as the target audience and the chosen functional unit should be stated.

The functional unit must be declared very precisely to avoid misunderstanding. For instance, it is meaningless to compare two different types of light bulbs with different lifespan and light intensity. A functional unit can be stated as *"lighting an office room with 1000 lumen for 1 hour"* or *"deliver 1 liter of clean natural water to a consumer"*. A functional unit defined in such a way allows comparison among different product/service systems. As a consequence, an LCA study has always to state conclusions in a comparative way such as *"product A is environmentally better than*

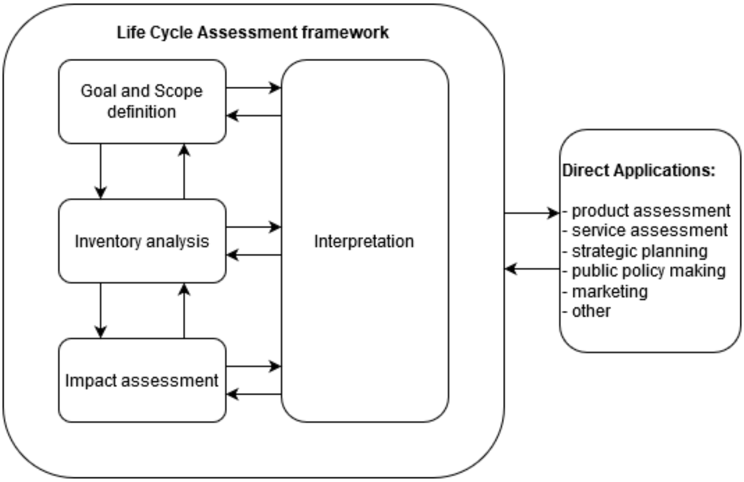


Figure 7.2: Methodological framework for LCA. According to ISO 14040. Source: ISO (2006a)

product B” or *“the production phase of product A is the most impactful during the life cycle”*. Absolute interpretations such as *“product A is sutainable”* are not correct conclusions and should be avoided.

Finally, the boundary conditions, impact categories and uncertainty analysis must be defined. Boundary conditions consist in defining which life cycle phases are considered (e.g. raw material extraction, transport, use, End of Life treatment) as well as any system expansion considered when circular practice such as recycling are analyzed. Boundary conditions in particular are necessary to allow meaningful comparisons with other or future studies. The impact categories consist in all the quantities one wants to monitor and evaluate such as $kgCO_2$, $kgSO_2$ and so on. The impact categories, typically, are aggregated into midpoint and endpoint indicators. The midpoints are direct environmental impact indicators such as Climate Change (CC) while the endpoints, generally, are aggregated indicators representing several midpoints, in order to elaborate a simpler result for decision and policy-makers.

Inventory

The Life Cycle Inventory (LCI) phase consists in *“the collection and the quantification of all inputs and outputs data for a product throughout its life cycle”*. The LCI phase is based on the so-called unit process (Figure 7.3), i.e. the fundamental and the smallest element which constitutes the product life cycle. For each unit process precise quantitative input and output must be identified. A unit process can be defined as the transport of products, the manufacturing of a plastic bottle, or the production of 1kg of pellets. The detail of the unit process depends on the goal and scope of the study. Inputs and outputs must be defined per unit of process such as *“10 kWh per 1kg of PET produced”* or “$1kgCO_{2,eq}$ *per 10 km of car travel”*. By defining the unit process, the basic hypothesis and limitations of LCA studies is that every process is linear. It means that input and outputs are linearly scalable (e.g. $1kgCO_{2,eq}$ per 10 km, $2kgCO_{2,eq}$ per 20 km). The task of quantifying all inputs and outputs for each unit process in many cases may be very challenging. Indeed, all unit processes can be connected in a straightforward linear chain or through more complex path of interdependency. In case of complex interconnections, a proper methodology for the allocation of inputs and outputs is necessary. When no available data exists for the upstream, or downstream, process a cut-off hypothesis can be introduced. A cut-off is an edge for the boundary condition of the system and may introduce uncertainties and approximations in the LCA analysis; thus, every cut-off must be clearly declared to facilitate the comparability with other studies and the reproducibility of results. For multi-input and multi-output unit processes, the ISO standard gives some advice to LCA practitioners for the allocation problem. It can be solved by a system expansions, i.e. by including outputs of a process not included in the analysis, by partitioning the output according to physical or economical parameters.

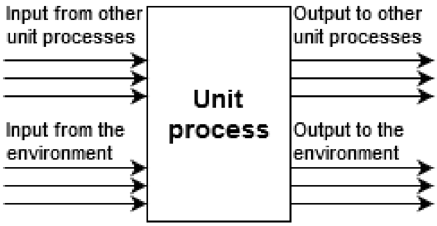


Figure 7.3: LCA unit process representation.

Impact assessment

The Life cycle impact assessment (LCIA) stage consists in evaluating and quantifying the environmental impacts of the whole life cycle analysed of a product/service system (Guinée et al., 2002). The impact assessment aim, in short, is to calculate the relevant impact categories starting from the output of the LCI phase by aggregating, normalizing, and weighting the output of all the unit processes identified in the previous step. There is a wide range of indicators and environmental impact measurements which can be evaluated through a LCA analysis related to circularity assessment, from Mineral Resource Depletion (MRD) and Fossil Fuel Depletion (FD) to Water Depletion (WD) and Agricultural/Urban Land Occupation (ALO/ULO). The general mathematical relationship between the outputs of the LCI phase to the impact category is expressed as (Guinée et al., 2002):

$$I_c = \sum_s CF_{c,s} \times m_s \tag{7.1}$$

where m_s is the amount of substance s in kg, $CF_{c,s}$ is the characterization factor for substance s and impact category c, and I_c is the indicator for category c. For instance, from the LCI phase an analysis can point out the amount of CO_2 and CH_4 produced during the life cycle of a product is 3 and 1 kg. In the LCIA stage, this quantities are aggregated into a common indicator, the Climate Change (CC), by multiplying the amount of emission for the related CF - 1 for CO_2 and 25 for CH_4. Thus, the CC indicator will be $1kgCO_{2,eq}/kg \times 3kg + 25kgCO_{2,eq}/kg \times 1kg = 28kgCO_{2,eq}$. Analogously, once several impact categories are quantified, these can be grouped and weighted to aggregate final results in a few indicators through the equation (Guinée et al., 2002):

$$W = \sum_{c} WF_c \times I_c \tag{7.2}$$

where WF_c is the weighting factor for the impact category c and W is the final weighted indicator. Typically, the impact categories represented by Equation 7.1 are called midpoint (e.g. CC) and the final weighted indicators (Eq. 7.2) are called endpoint (e.g. damage to Human Health) impact categories.

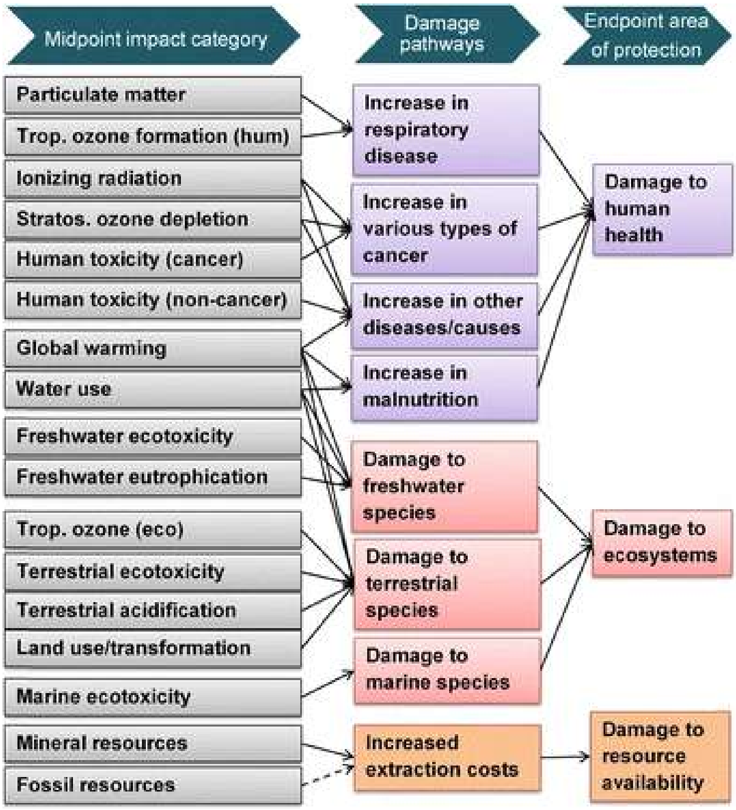


Figure 7.4: LCA Impact categories representation. Recipe method weighting process for a Life Cycle Analysis. Source: Huijbregts et al. (2017).

The ISO standard (ISO, 2006a; ISO, 2006b), in particular, defines several mandatory and optional steps for the impact assessment phase: 1) selection of impact categories, 2) classification, 3) characterization, 4) normalization, 5) grouping, 6) weighting, and 7) data quality analysis. The selection of impact categories and the classification steps are mandatory and consist in the *"assignment of LCI results to the selected impact categories"*. Normalization, an optional step, means to normalize the impact categories with respect to some reference values. Grouping and weighting, two optional steps, aim to aggregate the impact categories in a few final indicators, as represented by Eq. 7.2. To conduct a LCA study, generally, there exist several *methods* which relate the outputs from the LCI phase, to midpoint and endpoint impact categories.

One of the most adopted method is the so-called Recipe Method (Mark Goedkoop et al., 2013; Huijbregts et al., 2017), published for the first time in 2008 as a convergence between the CML (Guinée et al., 2002) and the Eco-Indicator 99 methods (M. Goedkoop et al., 1999). The CML method uses a midpoint approach for characterisation, while the Eco-indicator 99 focuses on the so-called endpoints. It consists in 18 midpoints[1] aggregated into 3 endpoints - 1. damage to Human Health (HH), 2. damage to Ecosystems Diversty (ED), and 3. damage to Resource Availability (RA) - as shown in Figure 7.4.

To evaluate the final results in terms of endpoints, the uncertainties from measurement, assumptions or from ignorance become fundamental. Uncertainties from the measurement regard errors in taking precise data or in evaluating them, uncertainties from assumptions consider different weighting procedures among indicators, while unvertainties from ignorance and from assumptions simply derive from a lack of knowledge about the evaluated process or product.

Generally in LCA studies (e.g. in the Recipe method) the Cultural Theory is used to weight differently the midpoint impact categories when grouped into the endpoint impact categories (De Schryver, Zelm, et al., 2011). LCA, and environmental science generally include three, out of five, perspectives from the Cultural Theory - individualist (I), hierarchist (H), and egalitarian (E) - in order to consider different stakeholders' visions of society. The individualist perspective reflects the viewpoint of industry, the hierarchist the institutional point of view (e.g. Environmental Protection Agency), while the egalitarian one, based on the precautionary principle, regards the societal environmentalism. The former two look at Nature as stable and in balance and at humans as highly adaptive. Thus, a short-term vision is considered by taking into account from a few decades (individualist) to hundred years (hierarchist). The latter, i.e. the egalitarian perspective, considers Nature as fragile and is more focused on the precautionary principle rather than on short-term impact evaluation (De Schryver, Sebastien Humbert, et al., 2013). According to Thompson (2005), the former two perspectives are risk-taken visions while the egalitarian one is risk averse. Table 7.1, as reported by De Schryver, Zelm, et al. (2011), summarized the main features of the three perspectives.

[1]The 18 midpoints are: 1. climate change (CC), 2. ozone depletion (OD), 3. terrestrial acidification (TA), 4. freshwater eutrophication (FE), 5. marine eutrophication (ME), 6. human toxicity (HT), 7. photochemical oxidant formation (POF), 8. particulate matter formation (PMF), 9. terrestrial ecotoxicity (TET), 10. freshwater ecotoxicity (FET), 11. marine ecotoxicity (MET), 12. ionising radiation (IR), 13. agricultural land occupation (ALO), 14. urban land occupation (ULO), 15. natural land transformation (NLT), 16. water depletion (WD), 17. mineral resource depletion (MRD), and 18. fossil fuel depletion (FD).

Table 7.1: Main features of the three world perspectives. Adapted from De Schryver, Zelm, et al. (2011) as described by the Cultural Theory.

Aspect	Individualist	Hierarchist	Egalitarian
Time horizon	20 years	100 years	Infinite
Including positive effects	Yes	No	No
Adaptation	Full	Mean	No
Future projections	optimistic	baseline	pessimistic

Interpretation

The interpretation phase is the last step of an LCA analysis and is defined by ISO standard as the phase where findings, in terms of impact categories and LCI output are evaluated with respect to the defined initial goal and scope to point out meaningful recommendations and conclusions (ISO, 2006a; ISO, 2006b). There are no very precise guidelines about the interpretation stage but the main aim is to evaluate the findings in relation to other sources and previous studies, as well as to identify the most impactful life cycle phases or unit processes.

7.1.3 Broadening the scope and the boundaries

Recently, to further advance and to *broaden the scope* of LCA analyses, as depicted in Figure 7.1, several improvements have been proposed in order to take into account the three sustainability pillars, and, thus, by including both social and economic aspects into the so-called Life Cycle Sustainability Assessment (LCSA) (M. Finkbeiner et al., 2010). A LCSA was, first introduced by Kloepffer (2008) as the sum of three separated components:

$$LCSA = LCA + LCC + SLCA \tag{7.3}$$

where LCA represents an environemntal LCA, LCC a Life Cycle Costing, and SLCA a Social Life Cycle Assessment. Despite the huge effort of the academic community in integrating the three sustainability aspects, i.e. environmental, economic, and social, in the past decade LCSA is still at its infancy due to the high complexity and interrelationship among impact categories. With respect to LCC hundreds of studies (Ayodele et al., 2020; Babashamsi et al., 2016; Foran et al., 2005; J. Li et al., 2019; Moins et al., 2020) have been conducted in the past decades by taking back the Life Cycle Thinking to its origin (Novick, 1959). Generally, LCC analysis are conducted alongside an environmental LCA study, or a social LCA, but rarely in an integrated way. Social LCA analyses (Kühnen et al., 2017; Petti et al., 2018; Sureau et al., 2018) may include various social aspects, from workers' right to inequality indexes (M. Finkbeiner et al., 2010) to even aestethic aspects (Sonetti et al., 2020). No standards or common criteria currently exist because, as previously mentioned, Social LCA is still at its infancy. Social aspects can be evaluated alongside economic and environmental ones or weighted and grouped together as represented in Figure 7.5. The aggregation process generally consists of a Multi Criteria Decision Analysis (MCDA). A MCDA is a complex weighting process among indicators, where preferences and weights are given in order to aggregate measurements, after a normalization step, with different unit of measures, e.g. Climate Change (CC) with Mineral Resource Depletion (MRD), that initially cannot be compared or summed.

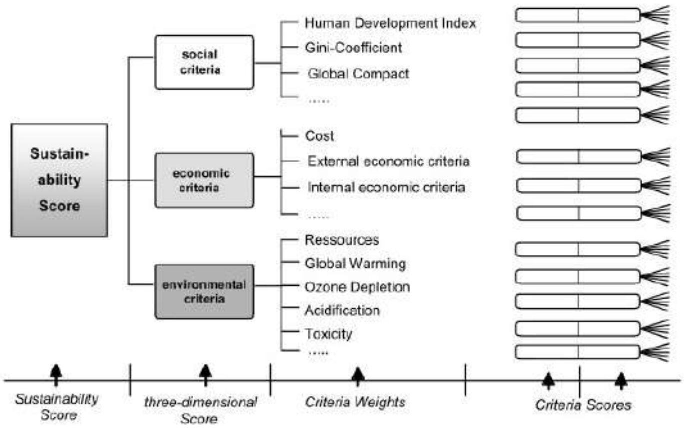


Figure 7.5: Sustainability Score weighting process for LCSA. Source: M. Finkbeiner et al. (2010)

On the other hand, *broadening the object of analysis* (with respect to Figure 7.1) means to enlarge the boundaries of the analyses to whole national economies or to a multi-regional scale. Currently, the widely adopted and recognized approaches to broaden the scope are the Environmentally Extended Input-Output-based LCA (EIO-LCA) and the hybrid LCA (Azari et al., 2018). The EIO-LCA method adopts annual Input-Output (IO) models (W. Leontief, 1986) in order to cope the process-based LCA limitations. It extends system boundaries to a whole national economy and overcome too specific results by using monetary values of the industry sectors, even if it produces sector-specific results. Finally, hybrid LCA mixes the two methodologies trying to optimize results by taking advantages from both techniques.

7.2 Input-Output Analysis

The Input-Output tables (IOT) have been introduced by V. W. Leontief (1941) in the Forties with the analysis "The Structure of the American Economy 1919–1929" as a statistical tool to evaluate all economic interchanges within the United States of America and all import and export with the rest of the world during the years of the II World War. The IOT mainly consists of a matrix linking the economic exchanges among the main industrial sectors of a country with the final consumer demand, and import and export for each sector. The resolution, i.e. the number of considered sectors, may vary from a few dozens economic sectors up to a few hundreds. Currently used and adopted by national statistic offices to evaluate several aspects of the economy of a country, thus for macroeconomic analysis, from the Gross Domestic Product (GDP) (Kunanuntakij et al., 2017) to the workforce (Santos, 2020), from impact of terrorist attack or natural disaster (Lian et al., 2006) to the national carbon footprint (Andrew et al., 2009), they are generally updated yearly. Every five years high resolution IOTs are released. Recently extended to include also environmental impacts, with the so-called environmental-extended IOT (EIOT) (Kitzes, 2013) and physical and energy exchanges with the environment (EUROSTAT, 2014) , IOTs have been also used to extend the boundaries of LCA studies with the so-called IO-LCA analysis (H. S. Matthews et al., 2015; Mattila, 2018) or the hybrid IO approach (Rocco et al., 2017) or to analyse precise and specific supply chains (Walmsley et al., 2014).

To understand the basic functioning of the Input-Output tables, it is necessary to look at economic transactions among different sectors within a national economy in a recursive and reiterative way. As described by Kitzes (2013), let's imagine to produce a hamburger. In order to produce it, it is necessary to have beef and wrapper. To breed a cow, feed and water are necessary, and for the wrapper one needs paper and plastics. Then, to produce feed, fertilizers, tractors, water, energy, or to produce the paper, pulp and water are necessary. One can imagine to continue indefinitely reconstructing every transaction within a country. Such transactions are exactly described by the input-output tables. More precisely the IOTs consist in several different tables.

Basically, the economic and physical exchanges are described by the 1) Supply and Use tables (SUT), or the 2) Symmetric, industry-industry or product-product, Input-Output Tables (SIOT) (UN, 2018). The supply and use tables define respectively the production and the consumption of products per economic sector, while the SIOT, which can be computed from the SUT, directly express the interchanges among industry sectors (industry-industry) or per product (product-product). Then, the IOTs link the interchanges with final consumer demand and with national import/export. Table 7.2 summarized the general SUT representation according to Haimes et al. (2005a).

Table 7.2: SUT input-output representation. Adapted from Haimes et al. (2005a)

	Commodity	**Industry**		
Commodity		Use Matrix (U)	Exogenous demand (e)	Total commodity output (y)
Industry	Supply Matrix (V)			Total industry output (x)
		Value added (w)		
	Total commodity input (y^t)	Total industry input (x^t)		

In general terms, using the elegant treatment of Haimes et al. (2005a), the use table $\mathbf{U} = [u_{ij}]$ is a $m \times n$ commodity-by-industry matrix interconnecting m commodities with n industry sectors, while the supply table $\mathbf{V} = [u_{ij}]$ is a $n \times m$ industry-by-commodities matrix and they are expressed as

$$\mathbf{U}=\begin{pmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,n} \\ u_{2,1} & u_{2,2} & \cdots & u_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{m,1} & u_{m,2} & \cdots & u_{m,n} \end{pmatrix}; \qquad \mathbf{V}=\begin{pmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,m} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n,1} & v_{n,2} & \cdots & v_{n,m} \end{pmatrix} \tag{7.4}$$

where the element u_{ij} represents the amount of commodity i *consumed* by industry j, while v_{ij} shows the amount of commodity j *produced* by the industry i. According to this notation the total commodity output y_i for commodity i is expressed as the sum over all industries j for each commodity i plus the corresponding exogenous demand e_i according to

$$y_i = \sum_{j\leq n} u_{ij} + e_i; \quad \forall i = 1,2,\cdots,m \tag{7.5}$$

while the total industry output for sector i is

$$x_i = \sum_{j\leq m} v_{ij}; \quad \forall i = 1,2,\cdots,n \tag{7.6}$$

Defining the summation vector $\Sigma = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix}$, equations 7.6 and 7.5 can be written as

$$\mathbf{x} = \mathbf{V}\Sigma; \tag{7.7}$$

and

$$\mathbf{y} = \mathbf{U}\Sigma + \mathbf{e} \tag{7.8}$$

where $\mathbf{e}$ is the exogenous demand vector. Following this treatment, all the elements are expressed in absolute term, i.e. with respect to the total of the economy. They can be simply normalized in terms of unit of output, i.e. per dollar of total output, by dividing per the total industry output $\mathbf{x}$ or commodity output $\mathbf{y}$ according to:

$$\hat{\mathbf{V}} = \mathbf{V}\left[diag\,(y)\right]^{-1}; \qquad \hat{\mathbf{U}} = \mathbf{U}\left[diag\,(x)\right]^{-1}; \tag{7.9}$$

where $diag\,()$ is the diagonal operator, i.e. a square matrix with the vector element on the diagonal. In other terms, each normalized element of the Use and Supply matrix is defined as $\hat{v}_{ij} = {}^{v_{ij}}/_{y_j}; \forall i,j$ or $\hat{u}_{ij} = {}^{u_{ij}}/_{x_j}; \forall i,j$.

The normalized SIOT matrix $\mathbf{A}$ (industry-industry or product-product), i.e. the so-called *technical coefficient matrix*, can then be computed simply by multiplying the normalized Use and Supply matrix as:

$$\mathbf{A} = \hat{\mathbf{V}}\hat{\mathbf{U}} \Leftrightarrow a_{ij} = \sum_k \hat{v}_{ik}\hat{u}_{kj} \tag{7.10}$$

Using the normalized definition of $\mathbf{U}$ and $\mathbf{V}$, the total industry output $\mathbf{x}$ and commodity output $\mathbf{y}$ can be expressed as $\mathbf{x} = \hat{\mathbf{V}}\mathbf{y}$ since $\mathbf{x} = \mathbf{V}\Sigma = \hat{\mathbf{V}}diag(\mathbf{y})\Sigma = \hat{\mathbf{V}}\mathbf{y}$ and as $\mathbf{y} =$

$\mathbf{U}\Sigma + \mathbf{e} = \hat{\mathbf{U}}diag(\mathbf{x})\Sigma + \mathbf{e} = \hat{\mathbf{U}}\mathbf{x} + \mathbf{e}$. Left-multiplying last expression by $\hat{\mathbf{V}}$ one can obtain $\hat{\mathbf{V}}\mathbf{y} = \hat{\mathbf{V}}\hat{\mathbf{U}}\mathbf{x} + \hat{\mathbf{V}}\mathbf{e}$, which can be rewritten as the well-known Leontief equation to express the interconnection between industry exchanges and consumer final demand $\mathbf{c}$

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{c} \tag{7.11}$$

where $\mathbf{c}$ has been defined as $\mathbf{c} = \hat{\mathbf{V}}\mathbf{e}$.

The technical coefficient matrix A, in input-output modeling, is of fundamental importance, since it allows to answer several different question in relative terms. By using the Leontief balance equation 7.11, it is possible to evaluate, for instance, how much wood it is necessary to have one unit of books for final demand, or, more in general, how all economic sectors will be affected by an increase in the agriculture sector? The technical coefficient matrix, obviously, can be also expressed in absolute term as

$$\mathbf{Z} = \mathbf{A}\mathbf{x} \Leftrightarrow a_{ij} = \frac{z_{ij}}{x_j}, \forall i, j \tag{7.12}$$

where z_{ij} represents the total input to the industry j from industry i. To better clarify the Leontief balance equation, in the focus 7.2 the rationale behind the equation is briefly discussed.

Focus 7.2 — Leontief Inverse: rationale of Leontief balance equation. The Leontief balance equation is a very useful and efficient tool for macro economic analysis as it includes reiterative and recursive exchanges among the economic sectors. The final demand $\mathbf{c}$ represents the amount of money spent by consumers while the value added $\mathbf{w}$ is the profit each sector has per year. Until now, nothing has been said about the fundamental hypothesis behind the input-output model. The input-output table assumes the economy at equilibrium, thus the total input (TI) must be equal, at any time, to the total output (TO). In this sense, equation 7.11 can be read as a balance principle and it can be written as

$$\sum_j z_{ij} + c_i = \sum_i z_{ij} + w_j = x_j \tag{7.13}$$

At the same time, it can be read as the sum of direct purchases from a sector and of all indirect purchases, i.e. second, and higher, order purchases made by all sectors which directly sell to such sector. This aspect can be directly seen by defining the Leontief inverse matrix. Equation 7.11 can be rewritten as:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{c} \tag{7.14}$$

$$\mathbf{c} = \mathbf{x}(\mathbf{I} - \mathbf{A}) \tag{7.15}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{c} \tag{7.16}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix. The Leontief inverse has a very precise meaning. Indeed, it represents the total requirement each sector needs to produce the final consumer demand $\mathbf{c}$, including first, second, and higher order purchases. This can be proofed by looking at the inverse $(\mathbf{I}-\mathbf{A})^{-1}$ which is the geometric series of $\mathbf{A}$, since each element $a_{ij} < 1$. Thus, Equation 7.11 can be rewritten as:

$$\mathbf{x} = [\mathbf{I}+\mathbf{A}+\mathbf{AA}+\mathbf{AAA}+\cdots]\,\mathbf{c} \tag{7.17}$$

The first terms, $[\mathbf{I}+\mathbf{A}]\,\mathbf{c}$ represents the direct purchases of each sector from itself and from direct supplier, while $[\mathbf{AA}+\mathbf{AAA}+\cdots]\,\mathbf{c}$ depicts the indirect purchases. For the sake of clarity, an example may clarify. To produce a book, it is necessary to buy paper, ink, and some work from the cultural sector (e.g. the writer). To produce the paper, pulp and water are necessary, to produce the pulp it is necessary to grow tree, thus water again is necessary. This chain may continue forever, reducing at each step, the contribution to the final output.

7.2.1 Environmentally-extended IOT

The input-output tables can be also used to assess environmental impacts at national level, like national carbon accounting (Andrew et al., 2009), as well as the impact of a particular and precise industrial sector. Let's define $\mathbf{B}$ the environmental matrix, i.e. a $q \times n$ matrix, where n are the number of economic sectors and q the number of types of different pollutants. Thus, the total pollutants per sector $\mathbf{m}$ can be computed (for each pollutant considered) according to

$$\mathbf{m} = \mathbf{B}\,(\mathbf{I}-\mathbf{A})^{-1}\,\mathbf{c} = \mathbf{Bx} \tag{7.18}$$

Thus, by multiplying the matrix $\mathbf{B}$, which represents the emitted pollutants per unit of output (e.g. \$) by the total industry output vector $\mathbf{x}$, the national environmental impact can be easily evaluated. With similar computation, thus, it is possible to expand the system boundaries of LCA studies by including emissions and pollutants up to second, third, and higher order, exchanges within a national economy, as described in the previous subsection. On the contrary, environmental assessment through the use of the input-output tables are very rough and less precise than bottom-up process LCA, and generally are used as preliminary assessment as pointed out by the EIO-LCA project of the Carnegie Mellon University (CMU, 2018). A simple example is provided in the focus 7.3. Further expansion has been developed for the input-output tables, as the Physical IOT (PIOT) or the so-called Physical energy flow accounts (EUROSTAT, 2014) but are out of the scope of this section.

Focus 7.3 — System expansion for Life Cycle Assessment. Let's suppose a simple economy with only two sectors, A and B, with a technical coefficient matrix

$$\mathbf{Z} = \begin{pmatrix} 7 & 4 \\ 5 & 3 \end{pmatrix}. \tag{7.19}$$

The final demand and value added vectors equal $\mathbf{c} = (3,4)$, $\mathbf{w} = (4,5)$ respectively. Thus, the total industry output can be easily quantified as $\mathbf{x} = (14,12)$, simply recalling $\sum_j z_{ij} + c_i = x_i$, i.e. a sum by column on the values of $\mathbf{Z}$. The normalized technical coefficient matrix can be computed by dividing each column of $\mathbf{Z}$ by the corresponding total industry output, according to eq. 7.12. Thus, $\mathbf{A}$ is

$$\mathbf{A} = \begin{pmatrix} 7/14 & 4/12 \\ 5/14 & 3/12 \end{pmatrix} = \begin{pmatrix} 0.5 & 0.33 \\ 0.36 & 0.25 \end{pmatrix} \tag{7.20}$$

Now, let's suppose an environmental matrix $\mathbf{B} = (8, 10)$ which represent the total amount of carbon dioxide produced by each sector in tCO_2 per year. By dividing for the total economic output per economic sector, the emissions per unit of output are $\hat{\mathbf{B}} = (8/14, 10/12) = (0.57, 0.83)$. At this point, the total intensity of emission, considering recursive exchanges within the economy, is quickly evaluated by multiplying the normalized environmental impact matrix $\hat{\mathbf{B}}$ by the Leontief inverse $\mathbf{L}$, obtaining

$$\hat{\mathbf{B}}\mathbf{L} = (0.57, 0.83) \begin{pmatrix} 1-0.5 & 0.33 \\ 0.36 & 1-0.25 \end{pmatrix}^{-1} = (0.508, 0.883)$$

in $tCO_2/\$$. Decomposing the Leontief inverse, into the geometric series, subsequent levels (1st order, 2nd order, ..) of impact may be evaluated. For instance the first order is simply $\hat{\mathbf{B}}\mathbf{I} = (0.57, 0.83) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = (0.57, 0.83)$, the second order is $\hat{\mathbf{B}}\mathbf{A} = (0.57, 0.83) \begin{pmatrix} 0.5 & 0.33 \\ 0.36 & 0.25 \end{pmatrix} = (0.583, 0.396)$, the third order $\hat{\mathbf{B}}\mathbf{A}\mathbf{A}$, and so on.
■

7.2.2 Input-output inoperability model

Finally, the input-output inoperability model (IIM) (Haimes et al., 2005a; Haimes et al., 2005b) has been originally developed by Haimes et al. to manage the risk of terrorist attacks in interdependent economic systems (Lian et al., 2006). IIM can be used to simulate the dynamics of a national economy in a wide range of scenarios such as critical infrastructure interdependency (Setola et al., 2009), disaster-risk analysis (K. G. Crowther et al., 2007), and manufacturing supply-chain risks (Brosas et al., 2017).

In the classic IO model, the equilibrium or as-planned production $\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ .. \\ x_N \end{pmatrix}$ of a country, or a region, is obtained from the interdependent productions of different economical sectors and the final demand $\mathbf{c} = \begin{pmatrix} c_1 \\ c_2 \\ .. \\ c_N \end{pmatrix}$ according to eq. 7.11 where

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & .. & a_{1N} \\ a_{21} & a_{22} & a_{23} & .. & a_{2N} \\ .. & .. & .. & .. & .. \\ a_{N1} & a_{N2} & a_{N3} & .. & a_{NN} \end{pmatrix} \tag{7.21}$$

is the interdependency matrix (eq. 7.10 in compact form), composed by elements a_{ij} that represent the production (output) of sector i required by sector j as input source. Thus, the production of sector i is given by the production of all sectors, each weighted by its respective interdependence a_{ij}, and the associated final demand, $x_i = \sum_j a_{ij} x_j + c_j$.

The IIM model extends the previous model to the case of recoverable productivity loss. If the production of one or more sectors is reduced because of an external incidence - such as a natural calamity or a governmental intervention -, a degraded production can be defined similarly to the equilibrium production as

$$\tilde{\mathbf{x}} = \mathbf{A}\tilde{\mathbf{x}} + \tilde{\mathbf{c}}, \tag{7.22}$$

If one defines $r = \tilde{x}/x$ as the production relative to the as-planned production ($0 \leq r \leq 1$), then $q = 1 - r = (x - \tilde{x})/x$ is the inoperability relative to the normal production ($0 \leq q \leq 1$), where $q = 0$ represents as-planned productivity and $q = 1$ its complete suppression). By subtracting Eq. (7.11) and (7.22) the inoperability $\mathbf{q}$ can be written as

$$\mathbf{q} = \mathbf{P}(\mathbf{x} - \tilde{\mathbf{x}}) = \mathbf{P}\,\delta\mathbf{x} = \mathbf{A}^*\mathbf{q} + \mathbf{c}^*, \tag{7.23}$$

where $\mathbf{P} = \mathrm{diag}^{-1}(\mathbf{x})$ is a transformation matrix, and $\mathbf{A}^* = \mathbf{P}\mathbf{A}\mathbf{P}^{-1}$ and $\mathbf{c}^* = \mathbf{P}(\mathbf{c} - \tilde{\mathbf{c}}) = \mathbf{P}\,\delta\mathbf{c}$ are the Leontief matrix and final demand reduction, respectively, after matrix transformation (Haimes et al., 2005a).

Sector inoperability

Assuming that the incident occurs at time $t_0 = 0$ causing the total suspension of sector i, $q_i(t_0) = 1$. As a consequence of the reduced production of sector i, the inoperability of the interconnected sectors, which was 0 until t_0, will rise at times $t > t_0$. In the dynamic version of the IO model, the production is obtained as a function of time as $\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{c}(t) + \mathbf{K}^{-1}\dot{\mathbf{x}}(t)$, where $\mathbf{K}^{-1}$ is the willingness of the economy to invest in capital resources (Miller et al., 1985). The differential equation can be written as

$$\dot{\mathbf{x}}(t) = \mathbf{K}\big[\mathbf{A}\mathbf{x}(t) + \mathbf{c}(t) - \mathbf{x}(\mathbf{t})\big], \tag{7.24}$$

where $\mathbf{K}$ is the *industry resilience matrix*. Similarly, then, the dynamic inoperability is written as

$$\dot{\mathbf{q}}(t) = \mathbf{K}\big[\mathbf{A}^*\mathbf{q}(t) + \mathbf{c}^*(t) - \mathbf{q}(t)\big], \tag{7.25}$$

or, in discrete form,

$$\mathbf{q}(k+1) - \mathbf{q}(k) = \mathbf{K}\big[\mathbf{A}^*\mathbf{q}(k) + \mathbf{c}^*(k) - \mathbf{q}(k)\big]. \tag{7.26}$$

For a stationary final demand, the general solution to Eq. 7.25 is

$$\mathbf{q}(t) = \mathbf{q}_\infty + e^{\mathbf{K}(\mathbf{I}-\mathbf{A}^*)t}[\mathbf{q}(0) - \mathbf{q}_\infty], \tag{7.27}$$

where $\mathbf{I}$ is the identity matrix. For $t \to \infty$, $\mathbf{q}(t)$ tends to $\mathbf{q}_\infty = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{c}^*$. Thus, the final or equilibrium inoperability is determined solely by the final demand.

Economic Loss

Once obtained the inoperability at different times, the total economic loss for sector i can be calculated as the as-planned production multiplied by the integral of the daily $q_i(t)$ over a defined period of time, i.e.,

$$Q_{loss,i}(T) = x_i \int_0^T q_i(t)\, dt, \tag{7.28}$$

where T is the defined final time.

Reduced air emissions

According to the Eurostat Manual Tukker et al. (2006), the total direct and indirect emissions of pollutants per sector can be computed according to eq. 7.18 as $\mathbf{Bx}$ where $\mathbf{m}$ is the $(1 \times n)$ vector of the total, direct and indirect, pollutant emissions, per sector, and $\mathbf{B}$ is the *intervention matrix*, a $q \times n$ matrix with the emission factor per million euro (in the case of Eurostat). q is the number of pollutant emissions considered (e.g. CO_2, NO_X, ...). Thus, by multiplying $\mathbf{x}(t)$ at each time-step, the dynamic of the total air emissions per sector can be obtained.

Similarly, the reduced air emissions per sector $m^{'}$, due to the inoperability, can be quantified by multiplying the matrix $B^{'}$ of the total emissions per sector for the inoperability (Eq. 7.27):

$$\mathbf{m}^{'}(t) = \mathbf{B}^{'}\mathbf{q}(t) \tag{7.29}$$

7.3 Environmental Product Indicators

The predictability of recoverable materials is of fundamental importance when designing, repairing and renovating, or recycling a product with a circular approach. This is particularly true for the built environment. Indeed, in the past decades, the amount of waste due to the demolition of buildings generated half of the global waste stream (Kibert, 2016). Dorsthorst et al. (2002) estimated that less than 1% of the existing buildings can be completely disassembled. Only in the last decade, researchers and practitioners focused on Design criteria and guidelines to improve the demountability of building components and products. Indeed, during the design phase of a product, service or building, more than 70% of the environmental impact can be determined and, consequently, prevented and minimized (Yarwood et al., 1998).

Design criteria are particularly important for the built environment because a building is a complex "object" made by different layers with different lifespan. Some very inspiring insights related to the material recoverability emerged in past decades. For instance, with respect to the six shearing layers of Brand (1995), each layer has to be thought to last from few years up to a hundred years (Stankovic et al., 2015): the site lasts forever, the structure from 30 to hundreds years, the skin at least for 20 years, the services between 7-20 years, the space plan and the stuff last not more than 10 years. Thus, it is fundamental to Design for Flexibility (DfF) or for Adaptability (DfAD) (Geraedts, 2016; Moffatt et al., 2001), for Disassembly (DfD) (Ciarimboli et al., 2007), for the Environment (DfE) (Yarwood et al., 1998) or for Reuse/Recycling (DfR) (Kriwet

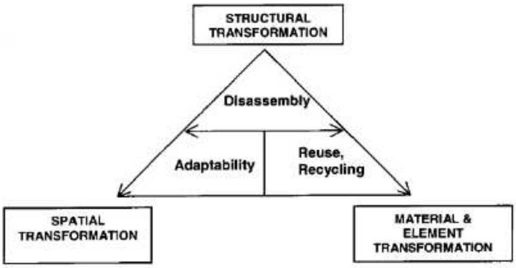


Figure 7.6: Key aspects of building transformation. Source: Elma Durmisevic et al. (2002)

et al., 1995) in order to substitute single components, products or materials without affecting other parts and layers as schematically shown in Figure 7.6. In general, DfX (X means Flexibility, Adaptability, ...) can be described as *"a combination of eco-design strategies including Design for Environment and Design for Remanufacture, which leads to other design strategies such as Design for Upgrade, Design for Assembly, Design for Disassembly, Design for Modularity, Design for Maintainability and Design for Reliability"* (Go et al., 2015).

Due to the large amount of aspects to be taken into account in a recovering/disassembly process, there does not exist yet standardized protocols or standards globally recognized. Many researchers have attempted to propose their guidelines, methodologies and criteria in the first decade of 2000s. For instance, Akinade et al. (2017) identified 15 factors for the Design for Deconstruction thanks to a thorough literature review. They aggregated the main 15 factors into 3 main groups spanning from environmental to social aspects as shown in Table 7.3: 1) material-related, 2) design-related, 3) site workers-related factors. A building circular assessment methodology has been also proposed based on

Table 7.3: Design factors for Design for Deconstruction. Source: Akinade et al. (2017)

Groups	Critical Factors for DfD
Material Factors	Specify durable materials, avoid secondary finishes, use bolts/nuts joint, avoid toxic materials, avoid composite materials, minimize building elements, consider material handling.
Design Factors	Design for off-site construction, use modular construction, use open building plan, use layering approach, use standard structural grid, use retractable foundation.
Site Workers Factors	Provide the right tools, provide adequate training.

Design for Adaptability by Geraedts (2016), named FLEXI. His methodology consists in calculating an adaptability score by multiplying two criteria, a weight F_i (shown in Table 7.4), and an Assessment Value V_i, for each layer and sub-layer of a building. The V_i consists in a weight between 1 and 4 given by a consultant/expert, where 1 represents a low adaptive capacity and 4 a high adaptive capacity.

Table 7.4: Weights for a Building Adaptative Index. Source: Geraedts (2016)

Layer	Sub-layer	Performance indicator	Weight
Site		Expandable site	1
Structure	Measurement	Surplus of building/floor space	4
		Surplus of free floor height	4
	Access	Access to building	2
	Construction	Positioning obstacles/columns in load	3
Skin	Facade	Facade windows to be opened	1
		Daylight facilities	2
Services	Measure & control	Customisability/Controllability	3
	Dimensions	Surplus of facilities shafts and ducts	4
		Modularity of facilities	2
Space Plan	Functional	Distinction between support & infill	4
	Access	Horizontal access to building	3

In recent years, to advance the general design principles, many researchers investigated specific indicators and key performance indicators (KPIs) to evaluate and assess the disassembly degree of a product. Environmental Product Performance Indicators (EPI) aim to indicate the macro, meso or micro features of a product. Macro EPIs can be compared to the simplest Circularity Indicators or to a partial LCA analysis result, quantifying environmental aspects, the amount of waste or energy losses. At the meso level, they evaluate aspects such as recyclable/reusable parts (with no indication of how to recognize them), while at the micro level they measure features such as the time for disassembly, the type of connections or the number of compound materials. Macro EPIs are useful tools for managers but they are simply a subset of the circularity indicators (see section 7.5) and LCA results. Meso and Micro EPIs, instead, are fundamental to precisely assess the product's recovering potential, i.e. the potential to recycle, reuse or remanufacture a product.

Regarding micro aspects, for instance, Durmisevic et al. (2006) defined the weights to be used for seven main DfD criteria as reported in Table 7.5. The weights can be obtained by answering some questions on design aspects, where 1 represents the best design solution and 0 the worst one in terms of disassembly potential.

The *functional decomposition* aspect evaluates in few words the separation of component functions. The *functional separation* weight is equal to 1 when the functionalities are completely separated, is equal to 0.6 when the functions are integrated but between components with the same lifespan, and, finally, it is equal to 0.1 (i.e. the worst weight) for integrated functionalities between components with different lifespan. The *functional dependence* aspect, instead, relates to the modularity of zones (e.g. pipes within a detachable false ceiling instead of within a concrete wall/pavement). The *Use life cycle* sub-aspect (*Life Cycle Coordination* aspect) evaluates the interconnection between two

Table 7.5: Durmisevic Design for Disassembly criteria. Source: Durmisevic et al. (2006)

Aspects	**Sub-aspects**
Functional Decomposition	Functional Separation Functional Dependence
Life Cycle Coordination	Use life cycle / coordination Technical life cycle / coordination Use life cycle / size
Relational Pattern	Position and type of relations Base element specification
Systematization	Structure and material levels Clustering
Assembly	Assembly direction Assembly sequences
Geometry	Geometry of product edge Standardization of product edge
Connections	Type of connections Accessibility to fixings and intermediary Tolerance Morphology of joints

components in terms of the lifespan. If both components have a similar lifespan the given weight is 1. On the contrary, if a component on a more durable layer (e.g. space plan) is strongly interconnected to a less durable one (e.g. stuff or services) the assigned weight is lower, since the more durable component is affected by a less durable one. The other two criteria, i.e. *Technical life cycle* and *Use life cycle / size* assess a similar aspect, with respect to the technical durability of components and of their size difference (e.g. a small component should not affect a big one). The *relational pattern* and the *systematization* quantify again the relation between different layer components, and the correct hierarchy among material, element, component, as well as element/component clustering according to functionalities or lifespan. The *assembly* criterium relates mainly to the *assembly direction* which aims to look at sequential assembly (weight = 0.1) versus parallel assembly (weight = 1). Parallel assembly represents components that can be detached independently from other, while sequential assembly refers to components that can be only disassembled after other components. This criterium is mostly related to the time for disassembly. Finally, the *geometry* and *connections* aspects mostly relate to the effort needed to detach a component - *geometry of product edge*, *standardization of product edge*, and *morphology of joints* - and to the potential damage made to detach a component - *type of connections*, *accessibility to fixings and intermediary*, *tolerance*. For instance, some of the *geometry of product edge* criteria are: 1) open linear (weight = 1), i.e. the component is free to be disassembled, 2) overlapping on one side (weight =

0.7), it means that one side of the component is partially blocked, or 3) insert on two sides (weight = 0.1), e.g. a windows with its frame. The *standardization of product edge* aims to point out if the edge is a standard one (weight = 1), which means that construction workers know how to detach it, versus geometry made onsite (weight = 0.1). Finally, the last criteria measure if the connection itself is reversible (e.g. bolts, nuts, pin) or not (soft/hard chemical glue) and if it is easily accessible without creating damage to other products/components. More in general, with respect to product, Cerdan et al. (2009) proposed a set of eleven general indicators to evaluate products, while Issa et al. (2015) provided a thorough open-access database of more than 250 EPI (macro, meso and micro), classifying them based on the life cycle stages - pre-manufacturing, manufacturing and design, distribution and packaging, use and maintenance, end-of-life, general activities – and based on the environmental aspects – materials, energy, solid waste, waste water, gaseous emissions, and energy loss. A short list of relevant EPIs, proposed by Cerdan et al. (2009), is reported in Table 7.6, while a partial selection - not exhaustive - of relevant EPIs classified into the two levels (meso and micro) from the provided database is shown in Appendix A.3.

Table 7.6: Environmental Product Indicators. Source: Cerdan et al. (2009)

Name	**Formula**	**Name**	**Formula**
Reusable parts	Weight of reusable parts / Total weight of product	Tools for disassembly	Number of necessary tools / Number of total joints
Recyclable parts	Weight of recyclable materials / Total weight of product	Time for disassembly	Total time to take apart all joints of a product
Reversible joints	Number of reversible joints / Number of total joints	Intelligent materials	Weight of clever materials / Total weight of product
Same material joints	Same material joints / Number of total joints	Laminated or compound materials	Weight of laminated or compound materials / Total weight of product
Parts with label	Number of parts with label / Total number of different parts	Painted, stained or pigmented surfaces	Painted; stained or pigmented surface / Total surface of product

Even if it is not possible to have a perfect estimation of which materials will be reused or recycled from design aspects, noteworthy information could be extracted. Indicators such as time for disassembly can provide an indication of whether the disassembly process is worthwhile, in economic terms (i.e. wage), while intelligent material indicates reversible materials for physical or chemical changes. The use of intelligent polymers and metals, for instance, is fundamental to reduce disassembly cost and time. If the use of some of the existing EPI is a best practice for designers and architects during the design phase of a product or a building, the same is not valid anymore for existing products/buildings due to lack of information. More "subjective" approaches can be applied to evaluate the feasibility of disassembling a component. For instance, Kroll et al. (1996) proposed a simple spreadsheet to assess the ease of disassembly. The designers evaluate a few design aspects, such as the accessibility, position, force, time and special features for each component of a product, with a subjective assessment, i.e. a score between 1 (easy) to 4 (difficult). The sum of all the assigned scores represents the ease of disassembly where lower score means easier task while higher score highlights the difficulties to disassemble. A similar approach was adopted by Yarwood et al. (1998) who developed a Design for Environment Toolkit and described in detail a Product Design Matrix to assess the environmental impact of a product during the design phase.

To wrap up, currently there exist many design methodologies and Environmental Performance Indicators to evaluate almost every single environmental or design aspect of a product or a component. This large amount of tools is one of the reasons behind the difficulty of having a unique standard; another reason is the fact that the reclamation audits still depend on the knowledge of the expert who conducts the audit. In general, the main advantages of design criteria are related to the micro/meso level. Indeed, as listed in Table A.3 in Appendix A.3 many EPIs are focused on a component level and since many micro level EPI are created for practitioners they guarantee a fast adoption. On the contrary, some limitations emerge because they depend on subjective feedback and the output of an evaluation gives a case-specific result. In particular, micro level EPI may provide useful information on the disassembly process but a robust relationship between the feasibility of disassembly (e.g. time for disassembly) and the effectiveness of recyclability is still a challenge. Meso-level EPIs lack of indication on disassembly but they can be used to quantify reusable, recyclable components. In conclusion, micro-level EPIs and well-specific design criteria may be adopted as a specific tool to evaluate the recovering potential of materials/components, while meso-level indicators may provide an effective monitoring tool.

7.4 Design for disassembly

The management of the End of Life of products is a fundamental strategy for eco-design in order to reduce environmental impacts, avoid waste of materials (C. M. Rose and Kosuke Ishii, 1999) and, eventually, to increase profit for manufacturing companies (Cappelli et al., 2007). In the past decades, several guidelines, best practices and approaches have been proposed to correctly manage the End of Life of products. Design for Disassembly (DfD) is one of the possible strategy to be followed by designers to easily and effectively allow product de- (re-) manufacturing and component recovering (Lowe et al., 2007). Disassembly is the *"systematic method for separating a product into its constituent parts, components, and subassemblies"* (Mandolini et al., 2018; Mitrouchev et al., 2015). DfD is a method that makes a product easy to disassemble (Ramani et al., 2010). It is the design stage in which the process, necessary tools and time to decompose single components or an entire product in single parts is planned in order to recover valuable materials and components (Henriques et al., 2017); indeed, DfD is the approach which makes possible closed-loop scenarios (Herrmann et al., 2008). Within the DfD framework, for instance, Henriques et al. (2017) proposed a set of indices to evaluate the disassemblability of a product and to assess the reusing, repairing, remanufacturing and recycling degree of a product in order to follow the 3R model. According to Ramani et al. (2010) the recovering of components and materials is not only an environmental issue but it fulfils three main purposes: 1) respect laws and regulations, 2) reduce environmental impacts, and 3) increase profit. The 10R model or the most common 3R framework point out the main approaches to manage closed-loop strategies. Each strategy, e.g. reuse or repair, relies on precise criteria, to be assessed, which allow a product, or a component, to be recovered. For instance, Henriques et al. (2017) proposed a set of indices to assess reusing, remanufacturing and recycling degree, plus energy recovery, of a product. Landfill has been discarded as possible strategy due to recent EU policies (EP, 2003). Each strategy has to be analyzed in detail in terms of social, economic and environmental impacts. Indeed, according to Zussman et al. (1994), the complexity and the economic and environmental value decrease from the product level (high complexity), towards the material/energy level (low complexity) passing through the component level (medium complexity).

Typically, the recovering potential is known and estimated by dismantlers and recycling centers, instead of designers or producers, as they represent the products' supply chain stakeholders in charge of the EoL phase (Lowe et al., 2007). According to Henriques et al. (2017), the main EoL costs, generally, are based on the following principal processes and phases:

1. disassembly,
2. cleaning,
3. reverse logistic, and
4. remanufacturing/regeneration.

On the contrary, the products' remanufacturing or the components' recovering permit multiple benefits for companies such as improved revenues due to the second-hand products, reduction of used virgin materials, costs and energy saving during the production process due to the recovered embodied energy in materials and components (Henriques et al., 2017). DfD criteria are particularly important both during the use phase, for maintenance, and the EoL phase; Lowe et al. (2007) pointed out some critical design factors such as the proper: 1) selection of materials; 2) design of components, and 3) choice of joints, connectors and fasteners. For these purposes, dozens of researchers and practitioners developed precise methodologies to assess the costs of disassembly and product EoL. For instance, Zussman et al. (1994), in the early nineties, proposed a utility theory, i.e. maximizing profit and no. or recovered components and minimizing landfill waste, to compare EoL strategies by considering as well economic and technical evolution of recovering processes. Germani et al. (2014) developed an approach to quantitatively assess the product disassemblability by calculating the time, and relative costs, to disassemble a particular product component based on the *Precedence Matrix*. The Precedence Matrix is a way to highlight the order that should be followed to disassemble the components of a product. The time, and costs, of each disassembly step was stored into a *Liaisons Knowledge DB* where each joint, for instance, has a corresponding precise disassembly time. Gungor et al. (1998) developed an algorithm to minimize tool changes during the disassembly phase. To evaluate the recovering potential, Ishii et al. (1993) defined the *clump*, i.e a sub-assembly which can be recovered without further steps.

In general, the most common approaches for DfD rely on the evaluation of the accessibility of joints, connections and fasteners, as well as on the assessment of the components' obsolescence and, economic and environmental, values. Economic value for recovering is related to the disassembly process which typically depends on the disassembly time, the easiest to be identified, and on other specific factors depending on products and processes.

7.4.1 Fundamentals of product design

Thinking about the products' EoL and the disassembly potential needs a few fundamentals related to product design, to available joints and connections as well as to intrinsic and external properties of components and products. Generally, the first requirements to be fulfilled for product eco-design are related, for instance, to the removal of hazardous materials, the reduction of pollutants and emissions during the life cycle or to the energy efficiency during the use phase (G. Johansson, 2008; Verberne, 2016). These requirements were originally addressed by the so-called Design for Environment (DfE) during the last decades of the XX century (Boks et al., 2007). Typically, the challenge for product design is to developed products by fulfilling environmental (e.g. low emissions), social (e.g. worker rights) or economic (e.g. low price) requirements meanwhile the function, i.e. the purpose, of a product is satisfied and maintained (G. Johansson, 2008). A function is, according to Roozenburg et al. (1995), the *"ability to bring about a transformation"*. To achieve such a challenging result, during the eighties and the nineties, researchers and practitioners investigated the elementary properties of products (Hubka et al., 2012; Roozenburg et al., 1995). A property, as stated by Hubka et al. (2012), is *"any characteristic of an object that belongs to and characterises it"*. According to Hubka et al., in their framework, the requirements can be completely determined by the elementary properties of a product. Then, the elementary properties determine the internal properties - i.e. the relationships between single components and the product properties - the external properties - i.e. the relationships between a product and its surrounding - and finally the product requirements, as depicted in Table 7.7.

Table 7.7: product design features. Source Hubka et al. (2012)

Product feature	**Description**
Product requirements	Law, regulations, longevity, maintenance, appearance, price quality, weight, functions
External properties	Reliability, manufacturability, ergonomic properties, aesthetic and operational properties, ...
Internal properties	Strength, manufacturing properties, corrosion, resistance, ...
Elementary properties	Structure, form, material, dimension, surface quality, tolerances, manufacturing methods, ...

For the same reason, other researches also investigated the Design for Disassembly basic properties (G. Johansson, 2008; Luttropp, 1997). For instance, Luttropp (1997) identified as elementary DfD properties the *ease of separation* which depends on the *"sorting borders"*, the enclosure of a precise sub-assembly or components with a particular function, and the *"separation surfaces"*, i.e. the surfaces where components or materials are separated, while G. Johansson (2008) pointed out four basic DfD internal properties - 1) *ease of identification*, 2) *accessibility*, 3) *ease of separation*, and 4) *ease of handling* -

which together defines the *"ease of disassembly"* external properties (the relationship between an object and its surrounding) and the *"efficient disassembly"* DfD requirements. According to G. Johansson (2008) the four internal properties for DfD are defined as:

1. the *ease of identification* represents how easily a specific component can be identified and it is mainly related on component location, form, product structure, dimension and product and DfD manuals;
2. the *accessibility* means the feasibility to physically reach a particular component and it depends on the location, orientation and the hierarchy of components.
3. the *ease of separation* highlights the actual physical process necessary to separate a component and it is affected, for instance, by the type of connectors and the tools needed,
4. the *ease of handling* reflects the property of grasping and moving the components and it depends on the dimensions, the form and the weight of a component.

Finally, for an efficient disassembly, according to Luttropp, the sorting borders and the separation surfaces should perfectly overlap. G. Johansson, instead, mapped each necessary action during the disassembly process with one of the basic properties. For instance, the orientation of a component, or of a connector, affects the ease of handling, as well as the "transferring" of it, directly affected by its weight; the loosening of connectors is related to the ease of separation, or the position itself influences the ease of identification and the accessibility. An efficient disassembly, then, depends on how easily, and in a time-efficient way, each action can be done. An efficient disassembly also depends on the EoL strategy (e.g. reuse or repair) since disassemblers should reach more in-depth components or materials. For instance, repairing and the maintenance of a product implies that only certain less durable components should be reached, while an efficient reycling needs to decompose complex objects into sub-assemblies composed by only a single material or a set of compatible materials. Indeed, according to A. Lambert et al. (2008), disassembly can be defined as *selective* or *complete* disassembly. Selective disassembly refers to the disassembly of a precise component or sub-assembly, while complete disassembly means the full product disassembly (Mandolini et al., 2018). Thus, to repair, maintain and remanufacture a product, DfD should focus mainly on selective disassembly, while for the recycling and energy recovering of materials the proper approach should be a complete disassembly. To evaluate an efficient disassembly process, current approaches basically focus on the evaluation of the *liaisons* (i.e. the connectors) and the necessary time to disassemble a target component or the whole product. The time for disassembly primarily depends on the *disassembly level*, i.e. the *"level in which one or more components/subassemblies connected to other components/subassemblies can be disassembled without any physical obstruction"* (Mandolini et al., 2018). To define the level of a component, Mandolini et al. (2018) stated two rules which must be satisfied:

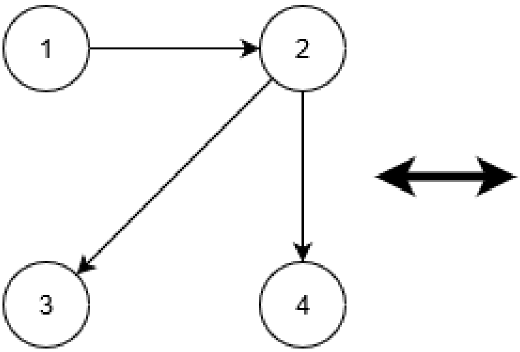
1. rule 1, *"if component A obstructs one or more components (e.g. component B) which are in relation only with component A, in case component A is removed at level n, the other components (e.g. component B) are free to be removed at level n + 1"*;
2. rule 2, *"if component C obstructs component B and component B obstructs*

component A, then component A is free to be removed after component B (direct precedence) and component C (inherited precedence)".

7.4.2 Time for disassembly

Evaluating the time for disassembly of an entire product (complete disassembly) or of a certain component of a product (selective disassembly) is fundamental to assess the feasibility of repairing, remanufacturing or reusing a product (Favi, Germani, Luzi, et al., 2017; Favi, Germani, Mandolini, et al., 2012). There are several aspects which can affect the time for disassembly as the level of the components (Mandolini et al., 2018), components' form, weight, size and needed tools (Kondo et al., 2003), connectors' types and direction (Popescu et al., 2013), and ageing of connectors (Yi et al., 2003), just to name a few.

Typically, to evaluate the time for disassembly, the best disassembly sequence planning (DSP) should be computed (Hengyu Wang et al., 2017). Several algorithms and methods have been proposed in the past decades. With respect to the algorithms, for instance, Srinivasan et al. (1997) identified the minimum number of components/connectors removal, Zwingmann et al. (2008) adopted the shortest path algorithm to identify the best disassembly path, while Galantucci et al. (2004) used a genetic algorithm. Regarding the methods, common approaches include the AND/OR diagram (Kara et al., 2005), precedence graph (M. R. Johnson et al., 1998; Mandolini et al., 2018) and interference matrix (Jin et al., 2013). Interference matrix is a method to calculate and consider possible interferences along the direction of extraction of components, while precedence graph is another matrix-based method to evaluate the level of disassembly for every component within a product. A precedence matrix is a $N \times N$ matrix where N is the no. of components of a product filled by 1 or 0. A value of 1 for row i and column j means that component j needs to be disassembled before component i, as shown in the example in Figure 7.7.



	1	2	3	4
1	-	0	0	0
2	1	-	0	0
3	0	1	-	0
4	0	1	0	-

Figure 7.7: Precedence Matrix example.

Mandolini et al. (2018), for instance, used the precedence matrix together with an ad-hoc prepared database (*Liaison DB*) with information about time for disassembly for most common connectors and some corrective factors due to aging, corrosion or the necessary tool. In their model, the effective time for disassembling a joint between two components is given by

$$T_e = T_s \prod_k CF_k \tag{7.30}$$

where T_s is the standard time to disassemble the joint, and CF_k is the corrective factor k . Then, the times for all the disassembly sequences were computed thanks to the precedence matrix and the optimum path was identified by looking for the minimum one. The time computed with these methodologies predict very accurately the real time for disassembly; for instance, the deviation between the time for disassembly computed with the Liaison DB proposed by Mandolini et al. (2018) and the effective real time during experiments and case studies was less than the 10%.

Cost for disassembly

With a similar approach Germani et al. (2014) also computed the total cost due to the disassembly process simply by multiplying the effective time for disassembly the component j ($T_{e,j}$) for the hourly labour cost C_l and the hourly tool cost (if any) C_{tool} according to:

$$\begin{aligned} C_j &= T_{e,j}\,(C_l + C_{tool}) \\ C_T &= \sum_{j=1}^{J} C_j \end{aligned} \tag{7.31}$$

where C_j is the cost for disassembly the joint j, J is the total number of joints for the product, and C_T is the total cost for a complete disassembly.

In general terms, the DfD costs depend on the EoL strategy - reuse/repair, remanufacturing, recycling, and energy recovery - and on the complexity of the target level - product, component, material, energy - as shown in Table 7.8.

Table 7.8: Complexity of EoL phases. Adapted from: Zussman et al. (1994)

	Reuse/Repair	**Remanufacturing**	**Recycling**	**Energy recovery**
Target Level	product	component	material	energy
Complexity	high	medium	low	low
Value	high	medium	low	near zero
DfD cost	high	high	low	near zero

7.4.3 Limitations

The quantification of the disassembly costs is not only fundamental for consumers who want to repair or to pay for the maintenance of their products but it is crucial also for the stakeholders involved in the EoL of the products such as the dismantler centers. Currently, existing DfD guidelines, DB and best-practices are known among designers and academics but there is still a lack of knowledge-transfer from designers to dismantlers and other stakeholders in charge of the EoL phase of products (Favi, Germani, Mandolini, et al., 2016). The knowledge-transfer issue from designers and manufacturers to dismantler and repairing centers has been addressed in recent years but only in general terms. For instance, Terazono et al. (2012) pointed out the benefit of spreading DfD information to EoL phase stakeholders, Das et al. (2001) proposed a standard protocol to be followed for knowledge-transfer to dismantlers, and Favi, Germani, Mandolini, et al. (2016) structured a Disassembly Knowwledge (DK) DB to aggregate all relevant information about product disassembly in order to facilitate the dismantler centers. Similarly to G. Johansson (2008), Favi, Germani, Mandolini, et al. identified a few issues for DfD which needs to be addressed because they affect an effective and efficient disassembly process - 1) assembly method and type of joints, 2) accessibility of components, 3) damages (aging, corrosion, ...) , 4) handling, 5) necessary tools, and 6) material separation (for recycling) - but an holistic framework to evaluate the whole DfD process is still missing. Moreover, with respect to the Design for Disassembly approach, there is still a lack of connections between general frameworks, such as the one proposed by G. Johansson (2008), and the effective percentage of repaired or maintained products (Favi, Germani, Mandolini, et al., 2016). Indeed, product repairing is done very commonly within second-hand markets of local artisans and generally data are collected through ad-hoc surveys (Fatimah and Wahidul Karim Biswas, 2016). Finally, disassembly assessment constitutes only one stage of the EoL phase of a product. For instance, as pointed out by Wahidul K Biswas et al. (2013) for a case study on remanufactured compressors, the remanufacturing process consisted in five steps: 1) disassembly, 2) cleaning & washing, 3) machining, 4) part replacement, and 5) assembly. In some cases, disassembly costs represent only a negligible percentage of the whole remanufacturing process (Fatimah, W. Biswas, et al., 2013).

To wrap up, Design for Disassembly criteria and methodologies to evaluate the feasibility of disassembling an entire product (complete disassembly) for recycling, or some target components (selective disassembly) for product repairing, maintenance, or remanufacturing were investigated in-depth in the past. However, within the circular economy framework, as highlighted by Kristensen et al. (2020) who reviewed 30 indicators for CE at micro level (i.e. at product level), currently the majority of indicators evaluate EoL recycling or remanufacturing strategies, but only a few indicators focused on disassembly.

7.5 Circularity Indicators

In recent years, the academic community made a great effort to propose and introduce Circularity Indicators (CI) in order to evaluate the environmental impact, the exploitation of virgin materials or the production of unrecoverable waste (EMF, 2015). New metrics have been introduced in order to assess the lifetime of products (Franklin-Johnson et al., 2016), the reuse potential (J. Y. Park et al., 2014) or the intensity of use (EMF, 2015). In 2019, Corona et al. (2019) published a literature review proposing a classification based on the 3E (Economy, Environment, Equity) of the most recognized Circular

Economy indices, indicators and frameworks[2]. They evaluated each method based on 8 requirements:

1. reducing input of resources,
2. reducing emission levels (pollutants and GHG emissions),
3. reducing material losses/waste,
4. increasing input of renewable and recycled resources,
5. maximising the utility and durability of products,
6. creating local jobs at all skill levels,
7. value added creation and distribution,
8. increase social wellbeing.

They concluded that none of the analysed methods fulfils all the requirements. Currently the largest categorized and ready-to-use database of circularity metrics has been developed by Saidani et al. (2019) who classified 55 Circularity Indicators considering the levels (micro, meso, macro), the type of loops (maintain, reuse/remanufacture, recycle) and several other criteria [3]. Finally, Parchomenko et al. (2019) classified 63 metrics through a Multiple Correspondence Analysis (MCA) by evaluating 24 features, mapping each metric into the Life Cycle Stage of a product/service. From their work, it is clear that none of the existing metrics allows to evaluate the whole Life Cycle and to take into accounts all relevant aspects of the CE.

Currently, the most recognized and worldwide adopted indicator is the Material Circularity Indicator (MCI) proposed by the Ellen MacArthur Foundation in 2015 (EMF, 2015). The MCI is represented in Figure 7.8 and it is based on three main parameters:

1. the amount of Virgin Material “V”,
2. the product Utility “X”,
3. the amount of unrecoverable Waste “W”.

More precisely, the amount of Virgin Material “V”, $V = M\left(1 - F_r - F_u\right)$, is equal to the total mass of the product “M” minus the fraction of reused material “F_u” and the recycled mass “F_r”. The product Utility “X”, $X = \left(L/L_{av}\right)\left(U/U_{av}\right)$, is computed by multiplying the lifetime ratio $\left(L/L_{av}\right)$, i.e. the product lifetime over the average lifetime of similar product in the market, for the intensity ratio $\left(U/U_{av}\right)$, the intensity of use per year over the market average. The amount of unrecoverable waste W, $W = W_0 + \left(W_F + W_C\right)/2$, is computed by summing the waste from the linear flow W_0 and the waste from the collection process W_C and from the recycling process W_F. Finally, the Linear Flow Index (LFI) can be

[2]INDICES: New Product-level circularity metric, Material Circularity Indicator (MCI), CE Indicator Prototype (CEIP), Global Circularity Metric, Circ(T), Circular Economic Value (CEV) and Circularity Index. INDICATORS: Circularity degree, Circular Performance Indicator (CPI), Eco-efficiency index, Eco-efficient Value Ratio (EVR), Global Resource Indicator (GRI), Longevity indicator, Resource Potential Indicator (RPI), Value-based resource efficiency (VRE) and Sustainable Circular Index (SCI). FRAMEWORKS: Input-Output Analysis, Material Flow Analysis, Life Cycle Assessment

[3]1) Levels (micro, meso, macro); 2) Loops (maintain, reuse/remanufacture, recycle); 3) Performance (intrinsic, impacts); 4) Perspective (actual, potential); 5) Usages (e.g. improvement, benchmarking, communication); 6) Transversality (generic, sector-specific); 7) Units (quantitative, qualitative); 7) Dimension (single, multiple); 8) Format (e.g. web-based tool, Excel, formulas); 9) Sources (academics, companies).

quantified as

$$LFI = \frac{(V+W)}{\left(2M + \frac{(W_F - W_C)}{2}\right)} \tag{7.32}$$

and the Material Circularity Indicator (MCI) according to

$$MCI = \max\left(0, 1 - LFI * \left(\frac{0.9}{X}\right)\right) \tag{7.33}$$

The LFI can be expressed in a simplified version by supposing $W_F = 0$, i.e. a recovering process 100% efficient (EMF, 2015), as

$$LFI = \frac{(V+W)}{(2M)} \tag{7.34}$$

while the MCI maintains the same formula. Thus, the MCI proposed by the EMF is a versatile indicator as it takes into account the exploited Virgin Material, the produced unrecoverable waste, and the product performance.

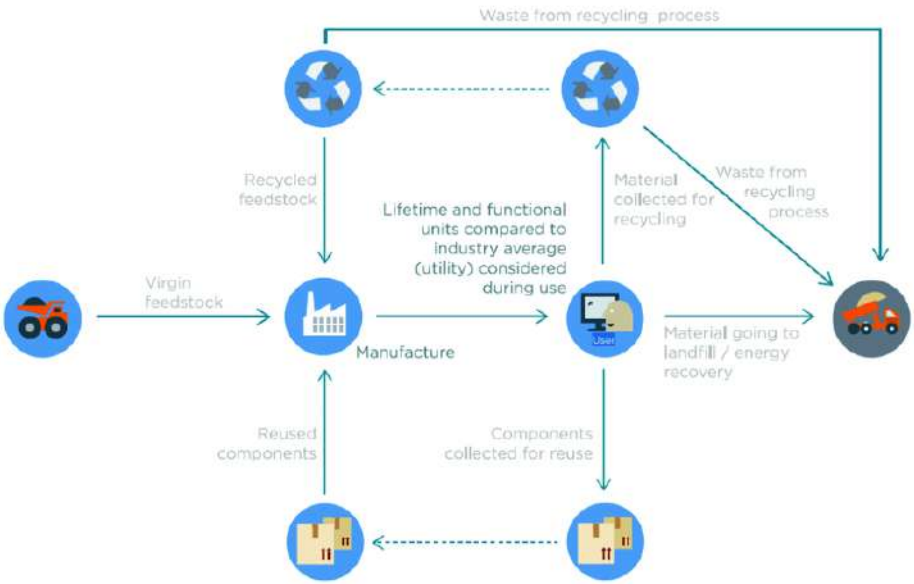


Figure 7.8: Material Circularity Indicator representation. Source: (EMF, 2015)

An improvement of the MCI, applied to the built environment, is the Building Circularity Indicators (BCI) proposed by Verberne (2016). The BCI is based on the MCI, computed for every product (doors, windows, tiles, furnishing, ...) of a building, and is improved by including design factors to “weight” the impact of each product in the environmental assessment of the whole building. A simplified representation of the

BCI is shown in Figure 7.9. Verberne in her model assumed some preconditions for sustainability as the minimization of the CO_2 footprint and the environmental impact or the maximization of the use of renewable energy and the material health. First, the MCI_p is quantified for each product within the building, where the subscript p represents the product p. Second, each MCI_p is weighted by multiplying the MCI_p for the seven identified disassembly factors F_i and the Product Circularity Indicators (PCI_p) is computed. Each factor consists in a weight between 0 and 1, where 0 represents the worst case for recycling (e.g. chemical connections) and 1 the best recycling potential (e.g. bolted connections). Third, the System Circularity Indicators (SCI) is calculated by weighting the PCI_p with the mass of each single product and, finally, the Building Circularity Indicators (BCI) is obtained by multiplying each SCI for the Level of Importance LK. LK is a weighting factor between 0 and 1, based on the Brand's six building layers (1995).

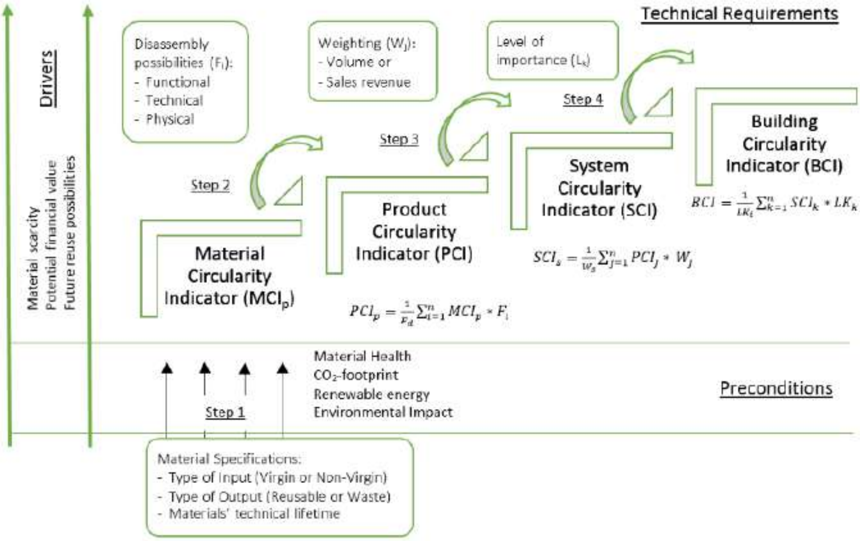
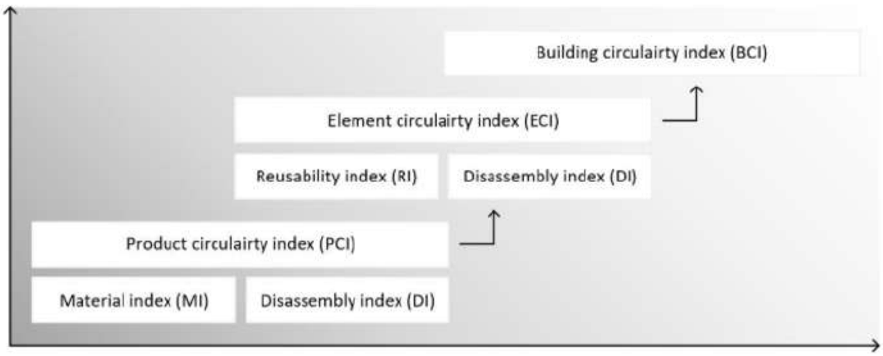


Figure 7.9: Building Circularity Indicator representation. Source: (Verberne, 2016)

More recently, some BCI improvements have been proposed. For instance, in 2018, a second version of the first BCI was suggested by Vliet (2018) omitting the building layers. In addition a third and a fourth version were discussed by Alba Concepts and by Schaik (2019). Alba Concepts developed a new BCI based on three levels, i.e. a Product Circularity Index (PCI), an Element Circularity Index (ECI) and a Building Circularity Indicator (BCI), while Schaik applied a slight modification of the Alba Concept indicator to building foundations. The proposed methodology is shown in Figure 7.10. The Product Circularity Index is computed by multiplying the Material Index (MI) for a Disassembly Index (DI), while the ECI is calculated by multiplying the Reusability Index (RI) for the DI. Finally, the BCI is evaluated by averaging every ECI for the analysed building. An element is defined by Alba Concepts as *"a clustering of products which are* *inseparably linked. When the connection is demountable and damage remains limited, the clustering ends and the elements are recovered"*. Practically, an element can be identified when a cluster of products has a PCI lower than 0.4. The DI is evaluated by following the Design for Disassembly weight shown in Figure 7.10.

Several other indicators are based on the same assumptions and, with other weighting formula or included factors, attempt to assess the same three main aspects. For instance, the Cradle to Cradle certification proposed a Material Reutilization Score (MRS) (Niero et al., 2019) to assess both the Intrinsic Recyclability (IR), i.e. the percentage that can be recycled, and the Recycled Content (RC), i.e. the percentage of material already recycled, according to the formula $MRS = {}^{(2*IR+RC)}/_{3}$. J. Y. Park et al. (2014) introduced the Resource Potential Indicator (RPI) to measure the intrinsic value for reuse for a material taking into account the state of art recycling technologies. Di Maio et al. (2017) suggested the Value-based Resource Efficiency (VRE) to assess the percentage of resource value embodied in a product/service that is returned after its life. The Longevity indicator, proposed by Franklin-Johnson et al. (2016), instead, indicates the total time that a material is retained into a product/service system.



1. Connection type	
Dry connection	1.0
Connection with additional elements	0.8
Direct integral connection	0.6
Soft chemical connection	0.2
Hard chemical connection	0.1

2. Accessibility of connection	
Accessible	1.0
Accessible with additional operations, causing no damage	0.8
Accessible with additional operations, repairable damage	0.6
Accessible with additional operations, with much damage	0.4
Not accessible, total damage to both elements	0.1

Figure 7.10: Building Circularity Indicator representation. Source: Alba Concepts and (Schaik, 2019)

To wrap up, currently, there exists a multitude of indicators attempting to assess different circularity aspects. Some indicators focus only on a certain feature, e.g. longevity or durability, recycled input or output, and have been adopted as managerial indicators or as part of product/service certification processes. Other indicators try to include social, economic and environmental aspects in a unique assessment process. Generally, such indicators are based on a LCA approach and are affected by the same consideration made for LCA analysis, i.e. the weighting system and the subjectivity of the measurements. In addition, a few approaches include both Life Cycle considerations and design criteria as the previously described Building Circularity Indicator. In conclusion, nowadays, a standardized methodology does not exist yet and the existing indicators proposed by researchers and practitioners are still under open debate in order to highlight and point out pros and cons. The main advantages of a circular assessment approach are to give more attention to the renewability of input resources, to focus more on the use-phase and the possibility to reuse, repair and remanufacture products, and to introduce the assessment of the potential recyclability of materials after product-life. Moreover, the Circularity Indicators generally need few input data and are quite easy to be computed. On the contrary, they could be criticized for a lack of scientific and rigorous approach, since many of them are simply based on material weight of the recycled/recyclable product parts or on the renewability/non-renewability of input resources, not taking into account the real environmental impact for renewable material production, embodied energy or CO_2 and so on.

7.6 Recursive assessment

Today the efforts towards the increase of reusing, repairing, or recycling practices are remarkable all over the world. At the legislative level, there is still a gap in terms of rules promoting good practices of recycling. Some of them have already been identified by previous research (Mariotti et al., 2019): taxes on the use of virgin materials or differentiated value-added taxes for recycled materials, the introduction of recycled content standards, targeted public procurement requirements, or recycled content labeling, just to name a few. Despite new recycling policies, promoting reuse remains the most effective solution to reduce the accumulation of waste. In fact, to ensure reusability, the first step is to encourage the deposit return system (Dario Cottafava, Riccardo, et al., 2019) as discussed in the case study presented in section 5.3 about circular business models. Although reusable products can successfully limit the use of virgin materials and can have a positive effect on the material extraction/production, the impact is not necessarily positive if other environmental indicators are considered. For instance, two recent studies on supermarket (Edwards et al., 2011) and grocery (Bisinella et al., 2018) shopping bags revealed how reusable cotton bags should be used thousands of times, i.e. dozens years of intensive use, to be environmentally better than equivalent single-use bags, which is clearly an unrealistic scenario. An effective approach for an objective evaluation of these indicators is given by the use of the Life Cycle Assessment (LCA) methodology.

LCA, as previously discussed in section 7.1, is one of the most adopted techniques to evaluate the environmental impacts of products and processes (Sonnemann et al., 2018). Several studies have evaluated the environmental effects arising from the reuse of plastic products, by comparing the same service offered by single-use products (J. Almeida et al., 2018; Garrido et al., 2007; Paspaldzhiev et al., 2018; Tua et al., 2019). However, what emerges from each LCA analysis is a snapshot of a precise situation, generally hard to be generalized (Ekvall et al., 2007; Finnveden, 2000), with specific boundary conditions, End of Life scenarios, or functional units. Indeed, nowadays, an open debate within the CE framework is emerging on how to model multi-cycle circular processes, including reuse, repair, refurbish, or remanufacturing (Amasawa et al., 2020). Dealing with different kind of products, i.e. electrical and electronic products, Ardente, Peiró, et al. (2018) highlighted the importance to consider all the operations needed to prepare an item for the reuse phase. Indeed a product, before being reused, could require minor interventions, that influence the assessment of the environmental impact. A similar study (Boldoczki et al., 2020) came to the conclusion that reusing laptops is not always preferable to recycling them. From an environmental point of view, if the impacts arising during a certain usage duration of a reused product are smaller than those of a new product, reuse is better than recycling. But this is not always the case: for instance, the global warming potential, cumulative energy demand, and water consumption impact categories, in the case of electric and electronic equipment, mainly derive from the use phase. In the same way, Simon et al. (2001), considering washing machines, attributed 90% of the environmental impacts to the use phase. In fact, the lifetime extension due to the repairing / remanufacturing / refurbishing is not always the best option, especially for energy-demanding products (Ardente and Mathieux, 2014). Moreover, more durable products may imply higher quality and amount of materials and, thus, a higher environmental impact during the production phase (Okumura et al., 2001). From the existing literature, it is straightforward that there is no single choice which is overall preferable in terms of single-use versus reusable products.

To point out such considerations, in case of reuse, repair, remanufacturng, refurbishing, several researchers proposed various models to identify an environmental break-even point (BEP) - i.e. the minimum no. of reuses after which a reusable product is environmentally better than the single-use equivalent one (Barletta et al., 2018). For instance, Silvia Bobba et al. (2016) proposed a set of environmental and economic indicators to evaluate product durability, starting from the indicator proposed by Ardente and Mathieux (2014), which takes into account lifetime, energy consumptions, impacts of lifetime extension and of the replacement product. Boldoczki et al. (2020), instead, proposed a simple linear model to compare the reuse of devices with the purchase of new ones, by evaluating the environmental impact versus the usage duration (time). With respect to plastics products, similar analyses have been carried out by J. Almeida et al. (2018), who compared a commercial reusable coffee cup with single-use cups, with the aim of identifying the environmental BEP. From the relevant literature, a standard methodology does not exist yet and, thus, the debate about robust formalisms to model multi-cycle closed-loop processes is still open.

To face up this issue related to environmental assessment through LCA, in this section a novel methodology for the interpretation of results is proposed, to facilitate the comparison between single-use and reusable products, presented in Dario Cottafava, Costamagna, et al. (2021). To easily identify the environmental BEP, the product efficiency - the efficiency of the production and End of Life phases - and the use efficiency have been introduced. The suggested formalism allows to decouple, in the BEP assessment, the effect of the use from the production and the EoL.

7.6.1 Break-even point assessment

To evaluate the BEP, let's define:

1. A = production, B = use, and C = EoL phase impact;
2. X = single-use, and Y = reusable product life cycle impact;

3. the subscripts 0, 1, 2, 3 refer to different scenarios;
4. the subscripts may also highlight the product material.

With this notation, for instance, B_{PLA,Y_1} is the impact of the use phase for a reusable product made of polylactic acid (PLA) for scenario 1. The subscript 0, for the use phase, represents the baseline, i.e. the use phase for the reusable product without loop.

Thus, the environmental impact of the whole cycle is denoted in general, skipping for the moment the materials' subscripts and considering only the baseline scenario without closed-loop (0), as X, for a single-use product, and Y_0, for a reusable product without loop. Thus, X and Y_0 are equal to:

$$X = A_X + B_X + C_X \tag{7.35}$$

$$Y_0 = A_Y + B_{Y_0} + C_Y \tag{7.36}$$

The use phase impact for the baseline, i.e. the life cycle without loop, has been considered equal to zero ($B_X, B_{Y_0} = 0$). According to this notation, three Key Performance Indices (KPIs) for a reusable product can be defined, as described in the following.

Product efficiency

The *environmental product efficiency for reusable products* KPI is defined as:

$$\eta_p = \frac{Y_0}{X} \tag{7.37}$$

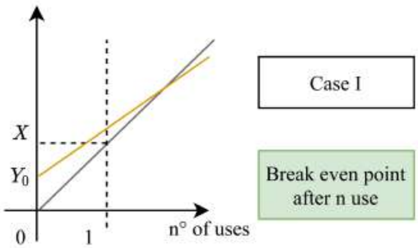
η_p is, in other words, the no. of single-use products which impacts as much as the reusable product and it represents the efficiency of the production and EoL process of the reusable product, with respect to a reference single-use product life cycle impact. Indeed, according to Okumura et al. (2001), a more durable product, such as a reusable one, implies a larger amount of materials and, thus $\eta_p > 1$. The larger is η_p, the less efficient is the reusable product related to the single-use one. If, $\eta_p < 1$, instead, it implies that the reusable product impacts less than the single-use product and it represents a very efficient production and EoL process.

Use phase efficiency

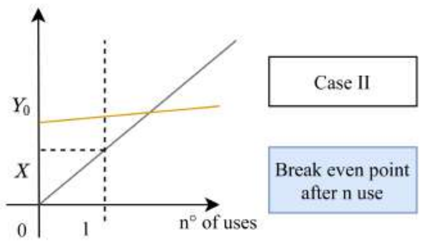
The *environmental use phase efficiency for reusable product* KPI is defined as:

$$\eta_{u,j} = \frac{B_{Y_j}}{X} \tag{7.38}$$

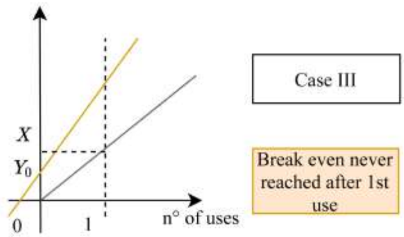
where B_{Y_j} is the impact of the use phase for the reusable product for the use scenario j. $\eta_{u,j} > 1$ means that the use phase for the reusable product B_{Y_j} impacts more than the whole life cycle of the single-use product X; thus, $\eta_{u,j} > 1$ represents an inefficient use phase. On the contrary, if $\eta_{u,j} < 1$, the use phase impact for the reusable product is lower than the single-use product life cycle and the smaller is $\eta_{u,j}$, the more efficient is the reusable product use phase with respect to the single-use product life cycle.



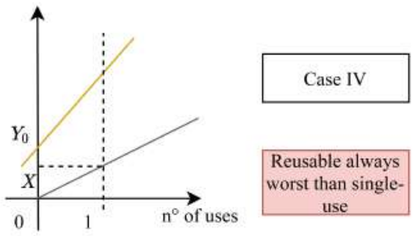
(a) Best case: efficient production and use phase.



(b) Normal case: inefficient production phase and efficient use phase.



(c) Limit case: efficient production phase and inefficient use phase.



(d) Worst case: inefficient production and use phase.

Figure 7.11: Environmental break-even point representation. Four possible cases comparing reusable and single-use products. The y-axis represents the related midpoint impact category. Gray lines refer to the single-use product, while yellow ones to the reusable product. Horizontal dashed lines show the impact X related to the whole life cycle of one single-use product, while the vertical ones refer to one use, i.e. $n = 1$.

Environmental break-even point

The *environmental break-even point* KPI is calculated as:

$$n_j = \frac{Y_0}{X - B_{Y_j}} \tag{7.39}$$

where n_j is the environmental BEP for the reusable product, considering the reuse loop scenario j. n_j represents the minimum no. of reuses necessary to balance the impact of the reusable product with respect to the same no. of single-use product usages. The proof and rationale of Eq. 7.39 is explained in focus 7.4.

Focus 7.4 — Proof of the break-even point formula. The *Environmental break-even point* is calculated as:

$$n_j = \frac{A_Y + C_Y}{X - B_{Y_j}} = \frac{Y_0}{X - B_{Y_j}} \tag{7.40}$$

where n_j is properly the environmental BEP for the reusable product, considering the reuse loop scenario j. n_j represents the minimum no. of reuses necessary to balance the impact of the reusable product with respect to the same no. of single-use product usages. Equation 7.40 can be simply proofed by declaring X_n, i.e. the impact of n_j single-use plastic products, as

$$X_n = n_j X = n_j (A_X + B_X + C_X) \tag{7.41}$$

and $Y_{n,j}$, the impact of a reusable product after n_j reuses for the use scenario j according to

$$Y_{n,j} = A_Y + n_j B_{Y_j} + C_Y \tag{7.42}$$

Then, by balancing the impact of n uses for both the single-use (Eq. 7.41) and the reusable product (Eq. 7.42)

$$X_n = Y_{n_j} \Rightarrow n_j X = A_Y + n_j B_{Y_j} + C_Y \tag{7.43}$$

equation 7.40 is proofed. ■

By substituting Eq. 7.37 and 7.38 into Eq. 7.39, the environmental BEP can be expressed in terms of the product efficiency η_p and the use efficiency $\eta_{u,j}$ according to:

$$n_j = \frac{\eta_p}{1 - \eta_{u,j}} \tag{7.44}$$

From equation 7.39, two cases emerge. If $X > B_{Y_j} \Rightarrow n_j > 0$; thus, n_j represents the minimum no. of reuses in order to obtain an environmental benefit for the reusable product with respect to the single-use. Otherwise, if $X < B_{Y_j} \Rightarrow n_j < 0$; thus, the reusable product never reaches an environmental BEP, since a negative number of usages is not possible.

Mapping cases

From Eq. 7.37, Eq. 7.38 and Eq. 7.39 (or Eq. 7.44) four possible cases may be identified which explain the behavior of the reusable with respect to the single-use product life cycle impacts. Figure 7.11 shows the four possible cases to compare reusable vs single-use products. The representation in Fig. 7.11 describes the environmental impact as function of the number of uses n. The slope of the straight line for the single-use product is given by X, while for the reusable product it is given by B_{Y_j}. With this formalism, the single-use line passes from the origin while the reusable line crosses the y-axis at Y_0, and if $X = B_{Y_j}$, n_j tends to infinite, as the two straight lines are parallel.

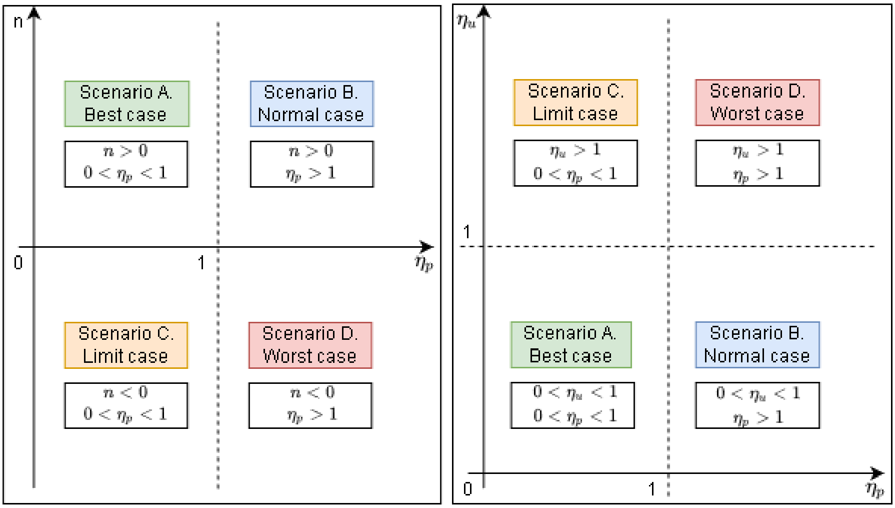
According to Table 7.9, each case corresponds to a precise condition for n_j, η_p and η_u such as:

1. *Case I: Best case.* This solution happens when $n_j > 0$ (or $0 < \eta_u < 1$) AND $0 < \eta_p < 1$; it implies that the reusable product is better than the single-use product after n_j reuses when $\eta_p > 1 - \eta_u$, while if $\eta_p < 1 - \eta_u$, the reusable product is always better.
2. *Case II: Normal case.* This case occurs when $n_j > 0$ (or $0 < \eta_u < 1$) AND $\eta_p > 1$; it means that the reusable product is better than the single use only after n_j reuses.

Table 7.9: Four cases and relationships with the n, η_p, and η_u

Cases	Environmental break-even point	Product efficiency	Use phase efficiency
Case I	$n_j > 0$	$0 < \eta_p < 1$	$0 < \eta_u < 1$
Case II	$n_j > 0$	$\eta_p > 1$	$0 < \eta_u < 1$
Case III	$n_j < 0$	$0 < \eta_p < 1$	$\eta_u > 1$
Case IV	$n_j < 0$	$\eta_p > 1$	$\eta_u > 1$

3. *Case III: Limit case.* This one represents the transition case and it occurs when $n_j < 0$ (or $\eta_u > 1$) AND $0 < \eta_p < 1$; it corresponds to a particular condition when the reusable product is better only before the first use phase.
4. *Case IV: Worst case.* Finally, this last case refers to $n_j < 0$ (or $\eta_u > 1$) AND $\eta_p > 1$ and it means that the reusable product is always worse than the single-use product.



(a) n VS η_p

(b) η_u VS η_p

Figure 7.12: Scatter plot representation of n, η_u, and η_p. Such representation may easily support the identification of worst or best cases for the comparison of reusable and single-use products.

Negative environmental BEP $n_j < 0$ has no real physical meaning but it is a useful KPI to classify the results within the discussed formalism. The four cases are represented in figure 7.12. Worst, best, normal and limit cases may be plotted into a scatter plot in terms of n VS η_p (fig. 7.12a) or η_u VS η_p (fig. 7.12b).

The four cases described in Table 7.9 and represented in Figure 7.12, if plotted, in logarithmic scale, in a scatter plot, correspond exactly to the four quadrants, i.e. best case ($\log(\eta_u) < 0$; $\log(\eta_p) < 0$), normal case ($\log(\eta_u) < 0$; $\log(\eta_p) > 0$), limit case ($\log(\eta_u) > 0$; $\log(\eta_p) < 0$) and worst case ($\log(\eta_u) > 0$; $\log(\eta_p) > 0$).

End of Life analysis

In order to analyze EoL scenarios is necessary to analyze distinctly a variation in the EoL of single-use products and a variation in the EoL of reusable products. In this subsection, subscripts refer to the EoL scenario. Thus, the use phase subscripts are omitted. A simultaneous variation of the EoL scenario of single-use and reusable products is out of the scope of this study.

Variation of EoL scenario of reusable products. First, if only reusable product EoL (C_Y) varies, this change affects only the product efficiency η_p (Eq. 7.37), since the use phase efficiency η_u (Eq. 7.38) does not depend on C_Y or Y_0. Thus, a change in the reusable product EoL, from C_{Y_1} to C_{Y_2}, induces a variation in the product efficiency according to:

$$\Delta\eta_{p,1\to2} = \eta_{p,2} - \eta_{p,1} = \frac{\Delta Y_{0,1\to2}}{X} = \frac{\Delta C_{Y_{0,1\to2}}}{X} \tag{7.45}$$

where $\Delta Y_{0,1\to2} = Y_{0,2} - Y_{0,1}$ is the variations in Y_0 from EoL scenario 1 (energy recovery) to 2 (recycling), while $\Delta C_{Y_{0,1\to2}}$ and $\Delta\eta_{p,1\to2}$ the corresponding variations, respectively in the EoL phase and in the product efficiency. The last step is allowed since without a variations in the production phase scenario, A_Y, $\Delta Y_{0,1\to2} = \Delta C_{Y_{0,1\to2}}$. Consequently, if $\Delta C_{Y_{0,1\to2}} > 0 \Rightarrow \eta_{p,2} > \eta_{p,1}$; in other words, as greater the EoL impacts is ($C_{Y_{0,2}} > C_{Y_{0,1}}$), as less efficient the product efficiency is. In terms of a scatter plot η_u vs η_p, an increase in the EoL impacts $\Delta C_{Y_{0,1\to2}} > 0$ implies a *right-shift* of the corresponding impact category, while a decrease in the EoL impacts $\Delta C_{Y_{0,1\to2}} < 0$ implies an analogous *left-shift*. Finally, a change in C_{Y_0} affects only when the BEP n is achieved but it does not affect if this is achieved or not, i.e. it does not modify the sign of n from positive to negative (or viceversa).

Variation of EoL scenario of single-use products. Similarly, a change in the EoL scenario of single-use product $\Delta C_{X_{1\to2}}$ can be described in terms of a variation of the product efficiency $\Delta\eta_{p,1\to2}$ and the use phase efficiency $\Delta\eta_{u,1\to2}$. In this case, both values vary. Indeed, since η_u is inversely proportional with respect to X:

$$\Delta\eta_{u,1\to2} = \eta_{u,2} - \eta_{u,1} = B_Y\left(\frac{1}{X_2} - \frac{1}{X_1}\right) = -B_Y\frac{\Delta C_{X_{1\to2}}}{X_1X_2} \tag{7.46}$$

an increase in the EoL impact for single-use products, $\Delta C_{X_{1\to2}} > 0$, implies a reduction in the use efficiency $\Delta\eta_{u,1\to2} < 0$, while $\Delta C_{X_{1\to2}} < 0 \Rightarrow \Delta\eta_{u,1\to2} > 0$. The same inversely proportionality holds for the product efficiency, according to

$$\Delta\eta_{p,1\to2} = -Y_0\frac{\Delta C_{X_{1\to2}}}{X_1X_2} \tag{7.47}$$

Thus, referring to the scatter plot η_u vs η_p, an increase in the EoL impact for single-use, $\Delta C_{X_{1\to 2}} > 0$, implies simultaneously a *down-shift* and a *left-shift* of the relative midpoint impact category, while $\Delta C_{X_{1\to 2}} < 0$ implies an *up-shift* and a *right-shift*. In terms of environmental BEP n, a change in the use phase efficiency, i.e. a vertical-shift, implies that n can change sign and in some cases a BEP cannot be achieved anymore, or on the contrary it can be achieved, depending on the relative differences $(X_1 - B_Y)$, or $(X_2 - B_Y)$. Since a change in sign in n between the two EoL scenarios 1 and 2 occurs if and only if $\frac{n_1}{n_2} < 0$, a quick indicator is the ratio

$$\frac{n_1}{n_2} = \frac{Y_1}{Y_2}\frac{(X_2 - B_Y)}{(X_1 - B_Y)} < 0 \Rightarrow \frac{(X_2 - B_Y)}{(X_1 - B_Y)} < 0 \tag{7.48}$$

because $Y_2, Y_1 > 0$ by hypothesis.

Limitation

The following treatment refers to eco-efficiency strategy and not to eco-effectiveness one. All the equations discussed in this section assume a positive slope of the lines which refers to negative environmental impacts for each use or reuse of a product. A similar treatment can be easily generalized by changing the initial assumption for $A_X, B_X, C_X, A_Y, B_Y, C_Y$ from being ≥ 0 to any possible value. A regenerative product / service, i.e. an eco-effective strategy, indeed, means that the impact of a single phase or of the whole life could be < 0 and thus the line could be with a negative slope. Although the generalization can be easy to implement, the consequence on the product and the use efficiency, and on the comparison between single-use and reusable products could be not straightforward. Thus, further development of the methodology should be addressed in order to include positive environmental impact (and thus negative slope).

7.7 Systems Dynamics

Systems thinking emerged in the Fifties and the Sixties and evolved in the past sixty years. It alludes to a modelling tool to analyze complex interrelated problems. Systems thinking aims at detecting and understanding the main causes which lead the dynamics of a system, over time and/or space, by identifying the relevant causal relationships and feedback loops. It is based on the use of the so-called *Causal Loop Diagrams* (CLD) revealing explicitly causes and relationships with graphs and diagrams (Hörđur V Haraldsson, 2004). System thinking is composed by two main sub-fields as depicted in Figure 7.13:

1. *System Analysis* (SA), the process to point out a model starting from relevant questions and tuning it in a reiterative way through simulation,
2. *System Dynamics* (SD), the simulation process to test, update and tune the model.

Background

Systems theory emerged at the beginning of the XX century where groundbreaking and visionary studies, such as the ones conducted by Alexander Bogdanov, introduced a theoretical framework named *Tektology* (from Greek tekton "builder") by considering living and non-living systems and their interrelationships to explore the dynamic evolution of a

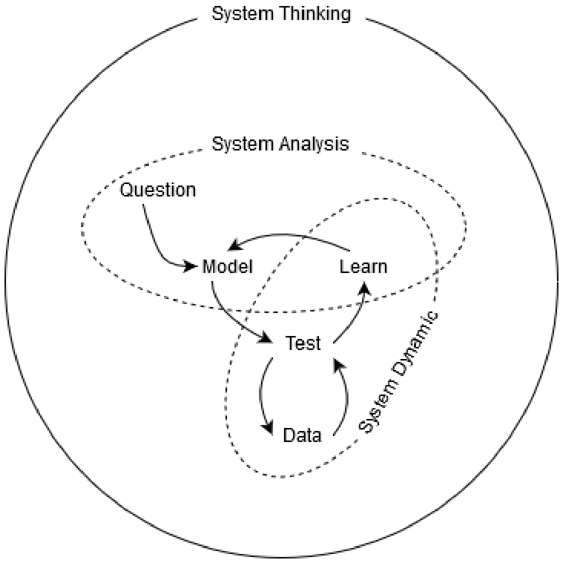


Figure 7.13: Systems thinking in a nutshell. Source: (Hörđur V Haraldsson, 2004)

system under variations of causes from outside, or inside. Originally, the word was used by Ernst Haeckel in its biological and zoological studies to describe how an organism is made by other organisms, i.e. the subsequent idea of hierarchical organization in system dynamics. Indeed, as a monist, he envisioned the world as a hierarchy of systems. Bogdanov was also the first one to introduce the concept of feedback, in its work named bi-regulator and defined as *"a system for which there is no need of an external regulator because the system regulates itself"*. Thus, he introduced implicitly the idea of the balancing loops in a system. Moreover, he introduced the idea of organized and disorganized complexity in systems by defining them respectively as *where the whole is greater/less than the sum of its parts* (Gorelik, 1983). A few decades later, in the 1940s, Ludvick von Bertalanaffy described the General System Theory (GST) and set up the fundamentals of the cybernetic movement (Hörđur V Haraldsson, 2004) founded later by Norbert Wiener and John von Neumann after World War II. Thus, the basic concepts of feedback loops (Mason, 1956) - i.e. a closed path where each variable appears only once per cycle - and self-regulation (Monique Boekaerts, 1999), already envisioned by Bogdanov, were developed during the Fifties, first in information and signal theories, and later adopted by the most general system dynamics and used in a wide range of disciplines. According to Zimmerman (2000), in psychology and cognitive science, self-regulation *"involves triadic processes that are proactively as well as reactively adapted for the attainment of goals* where a triadic process consists in a regulatory process, an interaction of *personal*, *behavioral*, and *environmental* processes, as depicted in Figure 7.14. The idea of a hierarchical organization of living and non-living beings as a central concept in system dynamics was further explored by Ilya Prigogine, Nobel prize for chemistry in 1977 for his studies about irreversible processes in thermodynamics and complex systems, who analyzed the dissipative systems in nature (Hörđur V Haraldsson, 2004). A dissipative system is an open system which remains far from thermodynamic equilibrium with the surrounding environment. This particular aspect is the golden rule in biology. Indeed, through self-organisation, living beings maintain their state far from equilibrium with respect to the surroundings moving towards a more complex state of the system in order to maintain their state (Prigogine et al., 1973). Then, the same concept of self-organization was largely debated by Maturana and Velana who introduced the term *autopoiesis*, i.e from Greek self-creation/production (Maturana et al., 1991).

Finally, from the Sixties to the present days, system dynamics was adopted in completely different fields as a multidisciplinary approach to solve complex problems from environmental science (D. H. Meadows, D. Meadows, et al., 1972), sociology (Burns, 2006) and economics (Jay W Forrester et al., 1976) up to cognitive science and psychology (G. B. Hirsch et al., 2007), passing through electronics and information theory (Karnopp et al., 2012).

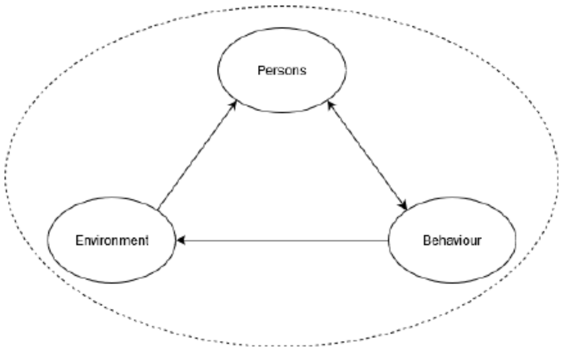


Figure 7.14: Triadic process in cognitive science. Source: (Zimmerman, 1989)

7.7.1 Fundamentals

System Dynamics concerns how to solve complex problems through the adoption of causal models. In the past, many policies, environmental policies first of all, failed due to a lack of understanding of the real causes of a particular problem (Hörđur V Haraldsson, 2004). Dynamic models are a useful tool to represent the interrelationships among variables and their causes. Static models focus on a precise snapshot, in time and space, of a real situation. For instance, linear correlations between two, or more, variables attempt to link together two given events typically missing causalities between them. This approach, especially in social sciences, may guide towards false positive findings. Indeed, as stated by Jeon (2015) *"regression analyses reveal relationships among variables, but do not imply that the relationship to be causal"*. SD, instead of static models, focuses on causal loops by investigating its behaviour over time through the effect of feedback loops or delays thanks to computer simulation (Hörđur V Haraldsson, 2004). The word simulation, indeed, derives from the latin *"simulare"*, i.e. "to imitate".

Thus, simulation should not include correlations, but causation, since correlations are a representation of the past.

In general terms, a system is a network of interrelated causal variables. The behaviour, i.e. the evolution over time, of a system can be analyzed only observing the system itself as a whole (Sterman, 2000). Since systems are organized in a hierarchical fashion, i.e. every system is composed by smaller sub-systems and is a sub-system of a larger one, boundary conditions are of fundamental importance in defining a model. By creating a model, it is also crucial to focus on the *dynamic complexity* and not on a *detailed complexity* (Hordur V Haraldsson et al., 2013). This is because, typically, our understanding has an optimum number of variables after which the general understanding decreases, as depicted in Figure 7.15. Identifying proper complexity and system boundaries requires to focus on the proper questions in order to reveal relevant causes and their relationships avoiding useless variables (Sterman, 2000).

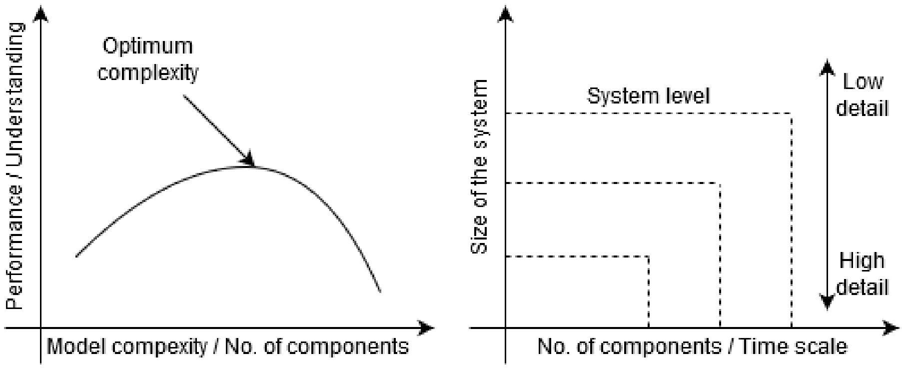


Figure 7.15: Performances and representations of SD models. Model complexity vs performance and system's size vs time scale. Adapted from: (Hordur V Haraldsson et al., 2013)

Defining the model

The first step to define a dynamic model and, then, to analyze it with the SD tools is to identify the main problem and rationalize it by declaring the most relevant variables involved and their scale. According to Sterman (2000) every relevant variable should be classified as:

- internal, i.e. interacting variable within the system boundaries,
- external, a variable which influences the system but it's outside the system boundaries,
- outside variables, the ones not considered in the systems.

Moreover, the level of interaction should be pointed out. In other words, every variable could change in a different time and space scale and it must be previously declared to simplify the subsequent modeling process. Figure 7.16 shows an example for a waste treatment plant as described by Hörđur V Haraldsson (2004). Thanks to such a preliminary classification and representation, it is possible to easily recognize which variables affect the decision-makers daily or monthly (e.g. waste production), as well as which ones have to be taken into account for a long-term policy planning (e.g. landfilling, capacity and population). This initial exercise is particularly useful in later stages of SD modelling as it points out the rationale and boundaries of variable interactions. Once identified the main relevant characteristics which can be done with the collaboration of experts and relevant stakeholders, the structure of the model should be created by identifying all possible interactions and feedback loops.

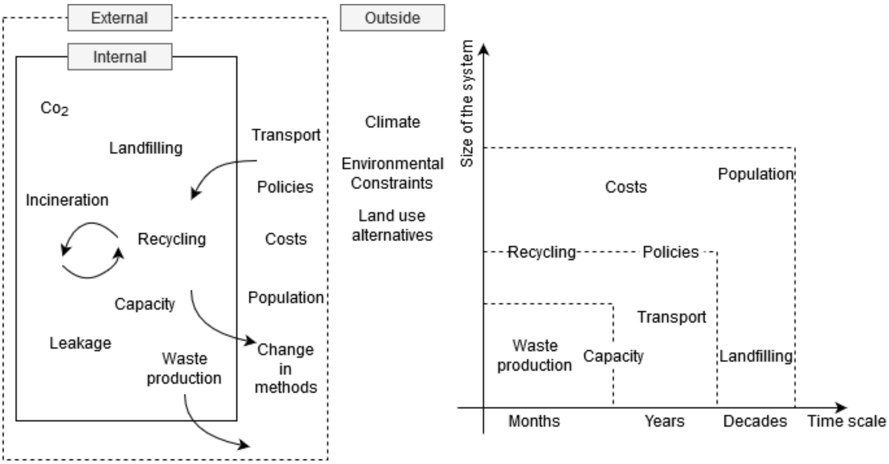


Figure 7.16: Classification of variables for solid waste treatment. Adapted from: (Hörđur V Haraldsson, 2004)

Exploring feedback loops

A SD model can be described and represented through a *Causal Loop Diagram* (CLD), first introduced and discussed by Jay W. Forrester (1961) in the Sixties. CLDs are a graphical way to represent causalities through feedback loops and to observe the non-linearity within a system. Causality is represented through arrows where the variable at the tail of the arrow affects the variable at the head, as described in Figure 7.17. A plus sign means that the two variables vary with the same sign; thus, if the tail variable increases, the head variable increases as well. On the contrary, a minus sign represents the opposite behaviour, i.e. if one variable increases, the other decreases and viceversa (Sterman, 2000).

In mathematical terms, the plus sign means $\partial B/\partial A > 0$, while the minus sign $\partial B/\partial A < 0$ (Sterman, 2000, chap. 5). With respect to the notation, a comment is necessary for CLD. Indeed, when an arrow connects a rate to a stock (e.g. birth rate to population) the interpretation is not straightforward. For instance, a decrease in the birth rate does not imply a reduction in population but it just means that the population will grow slowly and viceversa. For this reason, G. P. Richardson (1997) argued that the original notation for arrow, *s* for same direction, *o* for opposite direction, was not a proper notation.

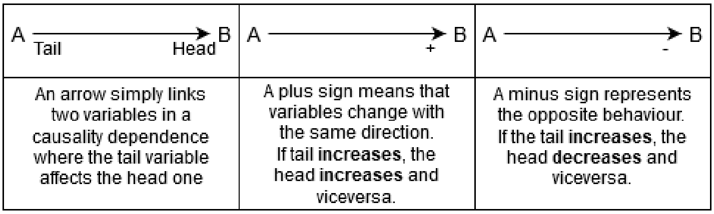


Figure 7.17: Arrow representation meaning for Causal Loop Diagrams. Source: (Sterman, 2000)

Through this notation, a feedback loop is simply a closed path between two, or more, variables. Basically, there exist only two types of feedback loops:

1. a *balancing loop*, typically represented with a B, is a loop which self-regulates the behaviour of a system,
2. a *reinforcing loop*, typically represented with a R, is a loop which amplifies some particular effects, generally resulting in an exponential growth of a variable.

The effects and results of a CLD on single variables are generally graphed over time in the so-called Reference Behaviour Pattern (RBP). A balancing loop induces a self-regulation system behaviour where the affected variables tend to an equilibrium point, eventually through fluctuations and oscillations. On the contrary, a reinforcing loop basically causes an exponential growth, moving the system far from equilibrium. Figure 7.18 shows the two elementary loops and their effect on system variables. On the bottom, a balancing loop and its effect on the system is represented, while on the top part a reinforcing loop and its exponentially growth, or decay, behaviour through time is shown.

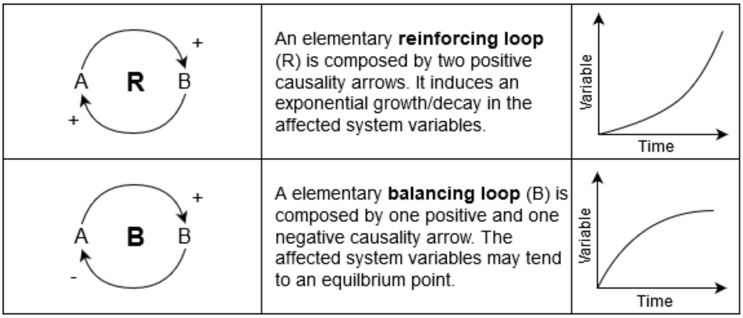


Figure 7.18: Elementary loop representation in causal loop diagrams. Source: (Sterman, 2000)

To evaluate the polarity of a loop, with n variables $x_1, x_2, \ldots, x_n$ the simplest way is to count the number of minus signs. If the number is odd, the loop has a negative polarity, and thus it represents a balancing loop. On the contrary if the number of minus sign on the causality arrows is even, the loop is a reinforcing one. Mathematically, the polarity of a loop can be computed by cutting a loop at any point, e.g. at x_1, according to:

$$\begin{aligned}\text{Loop Polarity} &= SGN\left(\frac{\partial x_1^O}{\partial x_1^I}\right) = SGN\left(\frac{\partial x_1^O}{\partial x_n}\frac{\partial x_n}{\partial x_{n-1}}\cdots\frac{\partial x_2}{\partial x_1^I}\right) \\ &= SGN\left(\frac{\partial x_1^O}{\partial x_n}\right)SGN\left(\frac{\partial x_n}{\partial x_{n-1}}\right)\ldots SGN\left(\frac{\partial x_2}{\partial x_1^I}\right)\end{aligned} \tag{7.49}$$

where x_1^O represents the output arrow from x_1 and x_1^I the input one.

All loops in a CLD basically follow one of the RBP shown in Figure 7.19 affecting system variables in a linear/exponential growth or decay in the case of reinforcing loops (R) or in an asymptotic behaviour towards an equilibrium point in the case of balancing loops (B). By combining multiple variables into a loop, or by combining multiple loops some more complex behaviour may emerge.

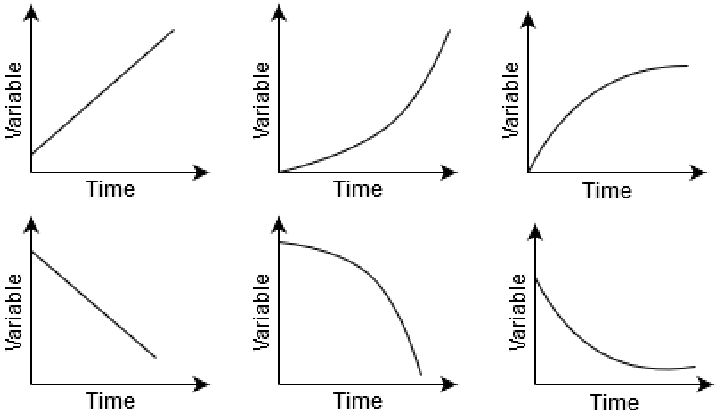


Figure 7.19: Reference Behaviour Pattern of elementary loops. Source: (Hörđur V Haraldsson, 2004)

Finally, fluctuations and oscillations of system variables may happen not only due to complex combination and induced effect of reinforcing and balancing loops but also due to the introduction of delays of some causality effects. IN CLD, delays are typically represented by a double stroke in the middle of an arrow. Generally, all systems are affected by delays (e.g. informational delays, material delays, decision delays, ...) which may cause non-linear behaviour. A typical example is the setting of a proper water temperature when one is having a shower. Indeed, when the water temperature is set, normally there is a delay due to the length of the water pipes before a user feels the effect of the water setting. This delay induces a decreasing oscillation around the desired temperature before the temperature perfectly fits with the expected one due to more and more small adjustments.

Stocks and flows

Stocks and flows, as already discussed in previous chapters, are of fundamental importance for socio-ecological and circularity studies. Despite their large adoption, simple causal loop diagrams are not able to distinguish between causal information arrows from stocks and flows (Morecroft, 1982). Thus, a new notation is necessary. Stocks are represented by rectangles, flows by pipes with a valve in the middle. Sinks and sources, outside the boundaries of the system are represented by a cloud, as depicted in Figure 7.20.

Figure 7.20: Stock and flow representation.

The basic difference between a general CLD and the stock and flow representation, as originally introduced by Jay W. Forrester (1961), is the conservation of the inflow and outflow. Indeed, as in water tubes, the same quantity of water enters through the inflow into the stock, as the water outflows from the stock. The stock acts as a temporary capacitor and container for the inflow, eventually creating some delay between the inflow and the outflow. In mathematical terms, a stock *integrate* or accumulate the differences between inflow and outflow according to:

$$Stock\,(t) = Stock\,(t_0) + \int_{t_0}^{t} [Inflow\,(s) - Outflow\,(s)] \tag{7.50}$$

where $Stock(t)$, $Inflow(t)$ and $Outflow(t)$ represent respectively the stock and the relative flows at time t. On the contrary, the instantaneous net change in a stock, i.e. the rate of change, is represented by the difference of the flows according to:

$$\frac{\mathrm{d}Stock(t)}{\mathrm{d}t} = Inflow(t) - Outflow(t) \tag{7.51}$$

In SD, stocks are particularly important since they are directly affecting the whole behavior and the dynamics of the system. According to Mass (1980), stocks affect the system mainly for the following reasons:

1. characterize the state of the system,
2. provide memory and give inertia to the system,
3. generate delays between the inflow and the outflow,
4. decouple the rate of inflow/outflow inducing disequilibrium in the system.

7.8 Limitation of current methodologies

Wrapping up, in this chapter several different methodologies and tools currently used for environmental assessment from micro to macro levels have been described. Although each one of them (except the novel circularity indicators) has not directly been designed to evaluate the circularity of products or processes, in recent years many previous methods have been adapted and slightly modified to face the current circular assessment challenge. Despite the effort of the academic community, none of them can be considered a satisfactory or exhaustive approach satisfying all the requirements to assess a circular *thing*, similarly to what emerged from chapters 5 and 6 from the most recent literature review about circular economy definitions. Each one has pros and cons and it can be successfully used to assess precise aspects related to the sustainability and the circularity.

LCA analysis can be both used at a micro or macro level, i.e. to evaluate the environmental impacts of products or processes or the effect of policy implementations. Similarly, LCC can be used to evaluate the costs of detailed production, use or EoL processes. Social LCA studies, the younger brother of life cycle analysis, are still under development and no standard exists. To homogenise environmental, economic, or social findings weighting process can be used, such as the multi criteria decision analysis approaches (Ishizaka et al., 2013), or the sustainability triangle (Kleine et al., 2009). Although largely adopted to support and help the decision-making process, any weighting and grouping process is highly debated due to the subjectivity in assumption (even if generally based on experts' opinion, or market benchmarking) and in the basic idea to compare and group variables with completely different meanings. The definition of the boundaries and of the functional units are another aspect open to debate in current LCA analysis. Generally, the boundaries in LCA analyses represent the framework of a study in order to allow comparability with other studies, but typically no absolute reference framework exists, e.g. in terms of the planetary boundaries or other absolute reference systems. Moreover, process-based LCA are highly dependent on the local contexts, e.g. precise enterprise processes, and generally findings are difficult to be generalized, as they provide a spacely and timely bounded snapshot of the real world. Finally, assessing process LCA studies with respect to a global absolute reference system was an unfeasible challenge until the recent study by S. Sala et al. (2020) who precisely quantified the planetary boundaries proposed by Rockström, W. L. Steffen, et al. (2009) in specific LCA impact categories.

To partially solve such limitations, input-output models can be used to expand the boundaries of LCA study, with the so-called environmentally-extended input-output based LCA or hybrid LCA (Azari et al., 2018) to national economy or to multi-national and global context (Marques et al., 2017). Although the high potentiality of the IOT in both economic and environmental analysis, generally the results are quite rough and with a low precision. An interesting aspect of the IOT is to allow to lead economic, environmental and social assessments (in terms of employment or consumer commmodities consumption for instance) at the same time. The same limitation on which reference system has to be adopted also exist for the IOT. Moreover, LCA and IOT, generally, do not connect environmental or economic impact to the design school of thought, although a few examples in the literature can be found (S. T. d. Almeida et al., 2017).

On the contrary, design researches generally evaluate products, or processes, performance in terms of the micro-property without a general vision, neither in terms of environmental boundaries nor in terms of economic system. Basically, the main indicators used to assess the circularity are related to the so-called Design for Disassembly criteria, i.e. the properties which allows to disassemble a product and thus to reuse, repair, or recycle it.

The novel circularity indicators, on the other side, seem to adopt a more systemic viewpoint by linking material flow analysis with environmental impacts or with the product properties. Still at their infancy, a few indicators, as the discussed Building Circularity Indicator, are attempting to link the micro aspects (e.g. design criteria) to macro features (e.g. the embodied energy or carbon) but the time dimension is almost absent from the encountered assessment methodologies. Indeed, LCA has no time dimension, if not in terms of scaling the impact categories related to the defined functional unit. In this sense, in recent years several studies addressed what I have defined recurrent assessment, i.e. environmental assessment based on the most basic functional unit (e.g. one use of an object), which allows to easily scale the findings and include closed-loop scenarios.

Finally, almost all methodologies are not based on causal explanations, if not widely intended as the interpretation of results phase of a study when explanations of underlying phenomena can be pointed out. For this reason, system dynamics, still under-developed in the framework of the circular economy, should be the approach to correctly connect the three pillars of sustainability (Leydesdorff, 2012) to precise design criteria, to the planetary boundaries and to the time dimension avoiding subjective weighting processes (e.g. the multi criteria decision analysis) or pure indicators for decision-maker without connection with effective impact (e.g. some of the novel circularity indicators).

In next part of this work, some detailed examples about a novel circularity indicator for the built environment, a LCA-based recurrent assessment about reusable and single-use cups, as well as a recent study conducted during the Covid-19 Pandemia based on the IOT to assess the economic and environmental impacts of the government restrictions in Italy during 2020 are briefly introduced to show the current limitations of present methodologies. At the end of the part III, finally, the fundamentals of a future information system which may take into account all the aspects discussed up to now will be provided in order to define what a *Circular thing* is and how to assess it.

Part Three. Theory Design

Theory into Practice

8. Applications

In this chapter, three examples/applications of current adopted methodologies (as introduced in chapter 7) for environmental and circularity assessment will be discussed in detail. The three applications consist of:

1. a comparative Life Cycle Assessment (section 8.1) between single-use and reusable cups by analyzing three use phases (onsite and offsite washing and handwashing), and two different End of Life scenarios (recycling/composting and energy recovery);
2. a circularity assessment (section 8.2) of seven buildings in Europe by the use of two circularity indicators, evaluating both embodied energy and carbon of in-use materials and their recovering potential thanks to design for disassembly criteria;
3. a dynamic input-output model (section 8.3), based on the inoperability theory (Haimes et al., 2005a), to assess the economic and the environmental impacts of the adopted restrictions in 2020 in Italy due to the Covid-19 pandemia.

Beyond exhibiting useful insights for traditional approaches related to environmental and circularity assessment, the three examples highlight how current existing methodologies are not satisfactory to assess circular objects in the broad framework of the CE, i.e. including the three sustainability pillars and considering the assimilative capacity of environment. Indeed, traditional approaches cannot properly evaluate a circular objects neither in terms of the boundaries of the system, e.g. the planetary boundaries, nor in terms of the needs of local, or global, population to identify the so-called *safe and just space for humanity* (Raworth, 2017). In brief, a general multi-level theory able to connect the micro with the meso and the macro levels, from the elementary elements of products (i.e. the materials and their impacts) and the recovering potential (through the use of design) to the *causal* impacts on society and the environment (e.g. by using the IOT) and to a dynamic equilibrium of the Planet (e.g. considering the planetary boundaries), is still missing.

8.1 LCA and recurrent assessment

The text of this section is largely based on and adapted from the paper "Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups" (Dario Cottafava, Costamagna, et al., 2021). In this section a LCA analysis example will be discussed with a simple model, introduced in section 7.6, to assess the impact recursively starting from an elementary functional unit, i.e. one use or reuse. In particular, this study shows a comparative LCA analysis between single-use and reusable cups made of different materials.

The following of this section is structured as follows. In section 8.1.1, the novel methodology is described by highlighting the differences with a traditional LCA analysis. In Section 8.1.2, the comparison between reusable and single-use cups is discussed in terms of the environmental break-even point. Finally, in Sections 8.1.3 and 8.1.4, the main results are compared with previous findings in the literature and some limitations of the proposed methodology are pointed out.

8.1.1 Methodology

The adopted methodology consists of two steps to further advance the well-consolidated LCA analyses and to support the results' interpretation for multi-cycle closed-loop processes where reuse, repair, refurbish, or remanufacturing are introduced. The first step consists of a traditional LCA analysis. The aim of the second step is to aggregate single impacts into the three main life phases (production, use, EoL) and to analyze, in terms of the number of uses "n", the environmental BEPs for each analyzed impact category as described in section 7.6 in chapter 7.

Case Study

The suggested methodology has been tested on a case study related to reusable and single-use plastic cups. The relevance of the case study was provided by analyzing the most common materials used, within the European Union, for single-use and reusable plastic cups. Four single-use cups, different materials, i.e. Polypropylene (PP), Polylactic acid (PLA), Polyethylene terephthalate (PET), and Cardboard + Polyethylene (PE) coat, have been compared with four reusable cups, i.e. PP, PLA, PET, and glass.

Seven relevant midpoint impact categories - Climate Change (CC), Ozone Depletion (OD), Acidification (A), Photochemical Oxidant Creation (POC), Eutrophication (E), Non-Renewable Energy Use (NREU), and Water Scarcity Indicator (WSI) - have been considered. Among the many possibilities of impact categories, as reported in the Technical Report by the Joint Research Center (JRC) (Fazio et al., 2018), CC and OD are recommended and considered satisfactory; A, E, and POC are also recommended, although they are not yet considered fully mature and satisfactory. In fact, more precise and in-depth studies are still needed to evaluate the weight of all characterization factors. As the system studied here presents a direct consumption of chemicals, water and energy both in the use phase and in the cups production, despite the lower reliability of the results, it was considered appropriate to measure the impacts also relating to the WSI and NREU categories.

For a comprehensive comparison between the service offered by disposable cups and reusable cups, different scenarios related to the use phase and EoL have been analyzed. Figure 8.1 shows a detailed scheme of the system life cycle, highlighting the considered scenarios. In particular, four scenarios for the use phase - 0) single-use without loop (baseline), 1) onsite washing, 2) offsite washing, and 3) onsite handwashing have been considered.

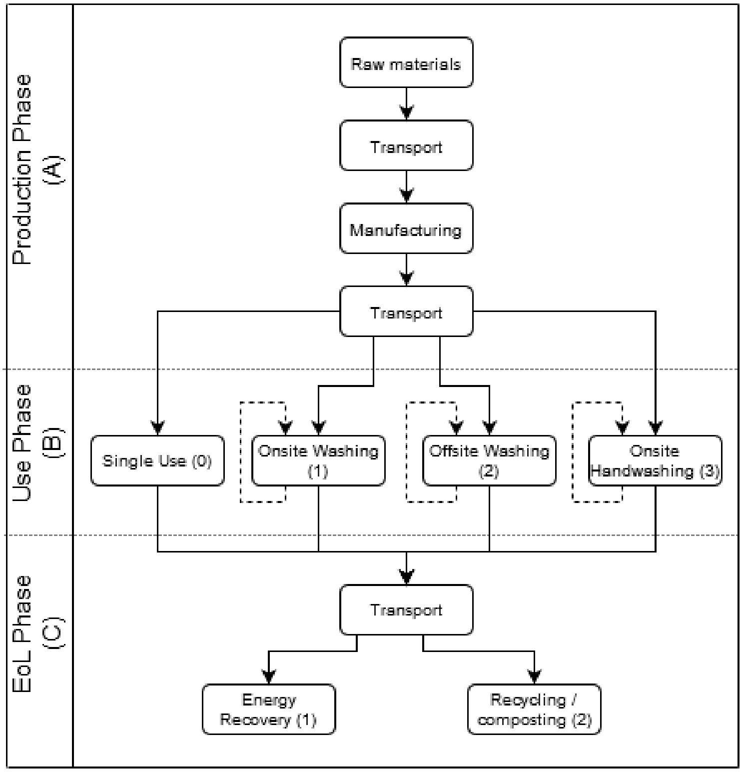


Figure 8.1: Overview of the analyzed scenarios.

The baseline 0) case consists of using the cup once and then throwing it away for disposal. The use phases have been modeled according to S. Martin et al. (2018) for 1) onsite handwashing, and 3) onsite washing with commercial washing machines. The onsite washing is modeled for the real situation, in which the bars/pubs/restaurants directly wash the cups. The 2) offsite washing refers to the use of industrial washing machines (primary data) and an increasing transport distance. It models real situations, such as temporary events, small bars without washing machines, or catering for buffets during events.

Finally, with respect to the EoL phase, energy recovery and recycling/composting have been compared. Landfill scenario has been discarded as a possible scenario, according to the Circular Economy European Directive (EP, 2020a). So, two scenarios have been considered: 1) 100% energy recovery, and 2) full recycling or, in the case of PLA cups, composting.

Life Cycle Assessment

LCA is defined by the International Organization for Standardization (ISO) standards 14040 and 14044. According to ISO, the LCA methodology consists of four conceptual phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and results' interpretation (ISO, 2006a; ISO, 2006b). The entire work was conducted with software SimaPro 8 and using the Ecoinvent v.3.3 database.

Goal and scope definition

The aim of this work is to assess the environmental BEP of deposit back systems for cups, by identifying the minimum number of uses a reusable cup needs in order to be considered preferable than a single-use cup. To achieve this goal, the LCA analysis was applied to the case of disposable and reusable cups in order to identify the main environmental impacts. These were later used to determine the break-even point between the two service delivery strategies.

The chosen functional unit was serving 0.4 liters of draught beverages in one go, which allows to collect the data relating to the service in a single supply. These data constitute the starting point for modeling and studying the function of serving beverages repeated *n* times over time (function performed by disposable and reusable cups). The system boundary has been defined considering the whole life cycle from the extraction of raw materials up to the EoL phase, as shown in Figure 8.1.

Life cycle inventory.

The weights of the cups considered in the study are summarized in Table 8.1. Weight of the single-use and reusable plastic cups, as well as of the glass reusable cups and single-use PE-coated cardboard cups, has been calculated as an average of available commercial products in Europe.

Table 8.1: Minimum, maximum, and average weight.

	Reusable cup [gr]				**Single-use cup [gr]**			
	PP	**PLA**	**PET**	**Glass**	**PP**	**PLA**	**PET**	**Card**
Min	35	150	60	330	6	7.5	8	7.5
Avg	40	175	70	360	7	8.5	9	8.5
Max	45	200	80	390	8	9.5	10	9.5

The sources from which all inventory values were derived or measured are reported in the Supplementary Materials of the corresponding published paper (Dario Cottafava, Costamagna, et al., 2021). The production of the plastic cups was modeled using the thermoforming and injection moulding processes for single use and reusable respectively (Changwichan et al., 2020; Crawford et al., 2020). Given the lack of specific data related to the production of PET cups, the system was modeled in a similar way to PP cups, taking into account the different physical-chemical properties of the polymeric materials. The input data for the packaging refer to reusable cups. As no specific data were obtained for the disposable cups, the system was left unchanged in the two cases.

To simplify the study and not to add variables that are not directly measurable, a distance of 100 km was assumed for the transport of raw materials to the production site of the cups. For the same reason, a distance of 1000 km between cup producer and place of use was considered. The latter is an average distance that allows covering the transport within single countries and between neighboring states in a territory such as Europe. Both transports have been modeled assuming a road service that uses freight lorries of 16-32 tons. Instead, the transport in the use phase, used in the offsite washing scenario, takes place with a light commercial vehicle.

The use phase has been modeled with reference to three different types of washing for reusable cups: hand washing, dishwasher, and industrial washing (offsite). The data used to model hand washing and dishwasher were obtained from S. Martin et al. (2018); the usage data of water, detergents, and energy were reported. The data for modeling an industrial washing were directly measured in an Italian crockery washing company. In the case of industrial washing, the contribution of round-trip transport was also considered.

The EoL scenario of incineration has been modeled for the cups in PP, PLA, PET, and cardboard+PE; as process output, the production of an amount of energy, specific for each material, was assumed. The alternative EoL's scenario considers the recycling of PP, PET, glass; to model the recycling process, the avoided production of a specific amount of raw materials, according to the percentages reported in the literature was taken in account, i.e. 85% of recycled polymer for PP and PET (Franklin Associates, 2018) and 89% of recycled material for glass (Gaines et al., 1994). PLA is not recycled, but it can be composted according to Vercalsteren et al. (2007).

Life cycle impact assessment

In this study, the environmental impacts are expressed as midpoint results and the considered impact categories are CC, OD, A, POC, E, NREU, and WSI.

The results of the first five impact categories were obtained using the EPD 2018 method (Environdec, 2019). In order to calculate the impacts, it refers directly to the CML-IA baseline method (for E, CC, OD) and CML-IA non-baseline method (for A). The EPD method was selected because of units of impact categories. In fact, for some raw materials (PP, PLA, PET, PE), the environmental impacts are usually obtained by the respective eco-profiles published in the literature, whereas eco-profiles calculated with the EPD method can be used directly. The results relative to the NREU impact category were obtained with the Cumulative Energy Demand (CED) method, which accounts for gross energy requirements (Frischknecht et al., 2007). For the WSI assessment, the Pfister et al. (2009) method has been adopted. This method allows to obtain geographically representative and accurate results.

Results' interpretation

For the last phase, interpretation of the results, an assessment based on the environmental BEP has been conducted, as described in the next subsection. In particular, the proposed approach supports the interpretation of results phase of LCA analyses. The introduction of the environmental BEP, the product efficiency and the use phase efficiency allows to decouple the effects of a change in the production phase (it affects only *"when"* the BEP is achieved) or in the use phase (it affects *"if"* the BEP is reached) by facilitating the comparison among reusable and single-use products. To evaluate recursively the environmental impacts and to compare the different cups the methodology introduced in section 7.6 in chapter 7 has been used.

Case study analysis

Materials. First, the four reusable cups (PP, PLA, PET, glass) have been compared with the four single-use cups (PP, PET, PLA, PE+cardboard) with respect to the seven impact categories (CC, OD, A, POC, E, NREU, and WSI). The considered EoL for all plastics cups and for single-use Cardboard+PE cups refers to 100% energy recovery (Vercalsteren et al., 2007), while for reusable glass cups EoL reflects recycling of 89% of the used materials (Gaines et al., 1994). The use phase refers to scenario 2 of Figure 8.1, i.e. offsite washing with 20km of transport roundtrip distance (10km+10km).

Transport distance. With the same EoL scenario (i.e. 100% energy recovery for plastic and cardboard cup, recycling of 89% of the used materials for glass), three different use phase scenarios for the reusable cups have been analyzed:

1. onsite handwashing (S. Martin et al., 2018);
2. onsite washing with commercial washing machines (S. Martin et al., 2018);
3. offsite washing with industrial washing machines and increasing transport distance.

An upper distance limit, i.e. the maximum number of km $n_{km,max}$ during the use phase to have a positive environmental BEP, for an infinite number of reuses, has been calculated by decomposing B_{Y_2} with respect to the washing impact $B_{Y_{2,washing}}$ and the transport impact per cup per km $B_{Y_{2,km}}$ according to:

$$n_{km,max} = \frac{X - B_{Y_{2,washing}}}{B_{Y_{2,km}}} \tag{8.1}$$

Eq. 8.4 (rationale in focus 8.1) shows how $n_{km,max}$ does not depend on the production and EoL phase of the reusable cups (since it's a constraint for the slopes). Thus, for all reusable plastic cups (with the same weight) the $n_{km,max}$ is the same.

Finally, the area of interest, in terms of the distance, was defined according to the following classification - 1) city (5km), 2) metropolitan area (30km), 3) district (80km), 4) region (200-300km), and 6) country (>400km).

Focus 8.1 — Rationale of the maximum distance. The upper distance limit, i.e. the maximum number of km $n_{km,max}$ for infinite uses during the use phase to have a positive environmental BEP, can be calculated by decomposing B_{Y_2} with respect to the washing impact $B_{Y_{2,washing}}$ and the transport impact per cup and per km $B_{Y_{2,km}}$ according to:

$$B_{Y_2} = B_{Y_{2,washing}} + B_{Y_{2,transport}} = B_{Y_{2,washing}} + n_{km} B_{Y_{2,km}} \tag{8.2}$$

where $B_{Y_{2,washing}}$ and $B_{Y_{2,transport}}$ are the washing impact per unit and the transport impact per unit for a distance of n_{km}, and $B_{Y_{2,km}}$ is the transport impact per unit per km. Thus, by imposing the constraint on the slopes, i.e. parallel straight lines,

$$\eta_u = \frac{B_{Y_2}}{X} = \frac{B_{Y_{2,washing}} + n_{km,max} B_{Y_{2,km}}}{X} = 1 \tag{8.3}$$

the maximum number of allowed km $n_{km,max}$ is:

$$n_{km,max} = \frac{X - B_{Y_{2,washing}}}{B_{Y_{2,km}}} \tag{8.4}$$

■

Dispersion Rate. The dispersion rate d was also briefly analyzed with the same use scenario (i.e. offsite washing with a roundtrip of 20km) and EoL scenario (100% energy recovery for plastic and cardboard cups, recycling for glass cups). d is defined as the average number of reuses before a reusable cup is dispersed and is substituted with a new one. Dispersed means that the use phase loop, whatever use strategy considered, immediately ends up, and the production of a new cup is considered. For the sake of simplicity, the EoL was considered the same as declared for the “not dispersed”.

EoL. Two EoL scenarios have been compared for the three - PP, PLA, PET - plastic cups: 1) 100% energy recovery, and 2) recycling. Composting, instead of recycling, has been considered for PLA. The variation in the EoL scenario has been analyzed for the use phase scenario $j = 2$, i.e. offsite washing with a roundtrip of 20km. The EoL for cardboard and glass cups has not been changed. Thus, 100% energy recovery and recycling of 89% of the used materials have been considered for cardboard and glass cups respectively. The methodology to analyse the EoL phase is described in detail in section 7.6.

8.1.2 Results

All midpoint impact categories for the production, use and EoL phases are reported exhaustively in the Supplementary Material of the original work (Dario Cottafava, Costamagna, et al., 2021) and in Table A.2 in Appendix A.2.

Materials analysis

Figure 8.2 shows the linear trend (lines) for the CC and the uncertainty due to the differences in the cup weights (shaded area), highlighting how the BEPs lie between 10 and 50 reuses in terms of CC depending on the material and the cup weight. Based on the relative position and the slope of the lines, the best single-use cup is the cardboard+PE coat, followed by the PP and PLA ones, while the worst one results to be the PET one. The cardboard+PE, PP, and PLA single-use cups CC impacts are very similar and the average impact (i.e. the solid lines) lie in the uncertainty shaded area. In particular, the PP single-use cup is comparable with both the cardboard+PE and PLA single-use, while the cardboard+PE can be considered better than the PLA one. With respect to the reusable cups, instead, after 50 uses, the best one is the PP cup and the worst the glass cup, even if its production and EoL impact is better than the PLA reusable cups and it is comparable with the PET cups, as shown in Figure 8.2. The PET (2nd best reusable cup) and the PLA (3rd one) cups lie in-between the PP and the glass cups. The slope differences among dashed lines mainly reflect the weight differences of the reusable cups (see Table 8.1), as a consequence of the carrying capacity during the transport of the use phase. Although the transport notably affects the use phase, all reusable cups achieve the BEP for the CC impact category for less than 50 uses.

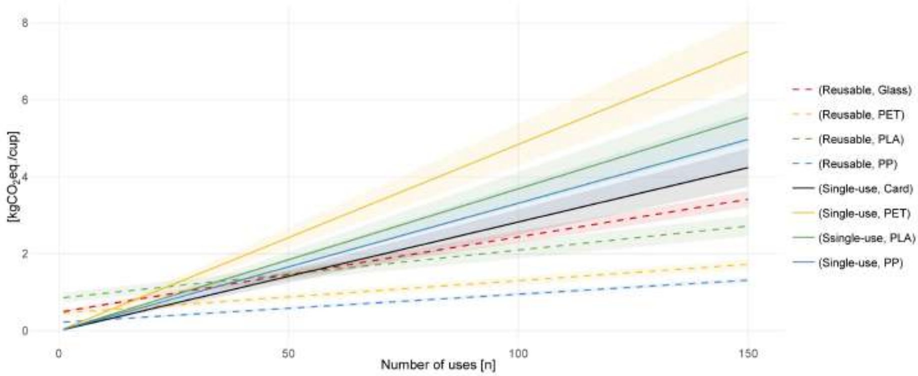


Figure 8.2: Climate Change (CC) for the offsite washing scenario. Scenario based on a transport distance of 20km during the use phase and energy recovery at EoL for plastic materials and recycling for glass. The shaded areas represent the uncertainty due to the minimum and maximum weights, while the line represent the average ones according to Table 8.1. Dashed lines refer to the reusable cups while the solid ones refer to the single-use cups.

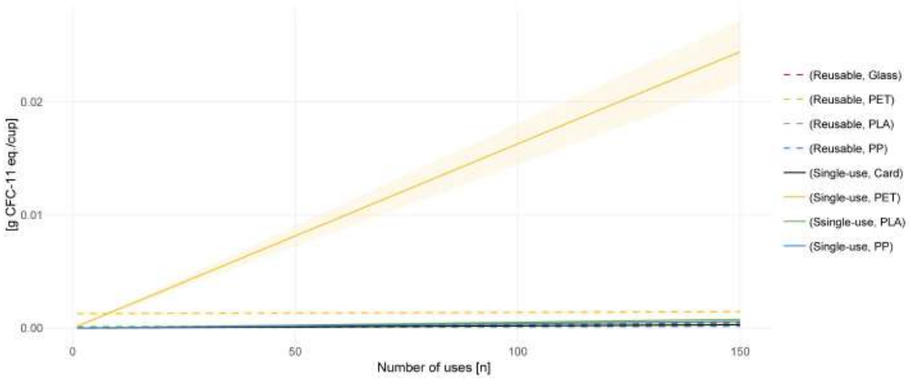
Table 8.2 summarize the BEP for the current section. All the plots regarding the impact categories are reported in figure 8.3. Fig. 8.3a shows that Only PET cups have a not negligible OD impact. The transport does not affect OD and such a big impact mainly derives from the production phase of the PET granulate (Plastics Europe, 2020). For this impact category, it turned out that the BEP for PET reusable cups is achieved for less than 10 uses.

The best solution with respect to the A impact category (Fig. 8.3b in the SI) is the single-use PP cup for any number of uses, while the worst solution, for high no. of uses, is the single-use PLA cup. A impacts for single-use PET and cardboard+PE cups are comparable, as evidenced by corresponding solid lines within the uncertainty shaded areas. Regarding the reusable cups, the best performance refers to the PP cups, followed by the PET cups, while the glass and PLA reusable cups are the worst ones. The bad performance of glass and PLA reusable cups is due both by a high impact during the production and EoL phase (see corresponding values at n=0) and by their high weight, which affects the use phase and thus the slope of the line. For this impact category, PP and PET reusable cups achieved the BEP for $n < 20$ with respect to all single-use cup types (avoiding the PP single-use cup), while PLA and glass reusable cups perform better than PLA single-use cup after 40 uses. Finally, PLA reusable cups, in comparison with the cardboard+PE and PET single-use cups, achieve the BEP after a large number of reuses ($n > 150$).

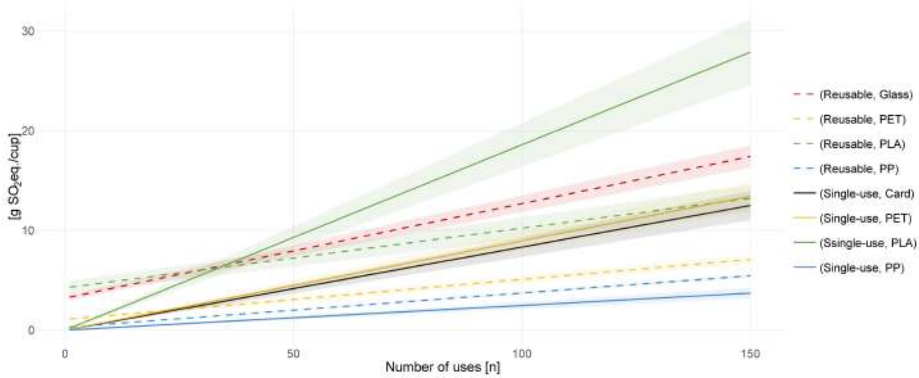
Table 8.2: Break-even point. Related to the offsite washing use phase and 100% energy recovery for plastic and cardboard cups and 89% material recycling for glass cups.

Number of uses to achieve the break-even point (BEP)								
Single-use cups	**Reusable cups**	**CC**	**OD**	**A**	**POC**	**E**	**NREU**	**WSI**
PP	**PP**	8	9	-29	61	-4	9	-5
	PLA	41	57	-121	-164	-73	39	-61
	PET	18	472	-70	-2631	-21	21	-49
	Glass	35	80	-46	-30	-16	42	-17
PLA	**PP**	7	6	2	2	1	10	3
	PLA	35	35	34	33	36	43	41
	PET	16	324	7	19	8	23	29
	Glass	28	31	35	24	13	50	15
PET	**PP**	5	0	5	1	12	6	1
	PLA	24	1	143	15	1571	22	16
	PET	11	8	22	10	74	13	12
	Glass	17	0	-630	9	-78	18	5
Cardboard +PE	**PP**	10	25	6	8	7	23	9
	PLA	54	667	181	350	284	151	184
	PET	23	1472	25	82	39	54	109
	Glass	55	-60	-285	-67	-320	-235	106

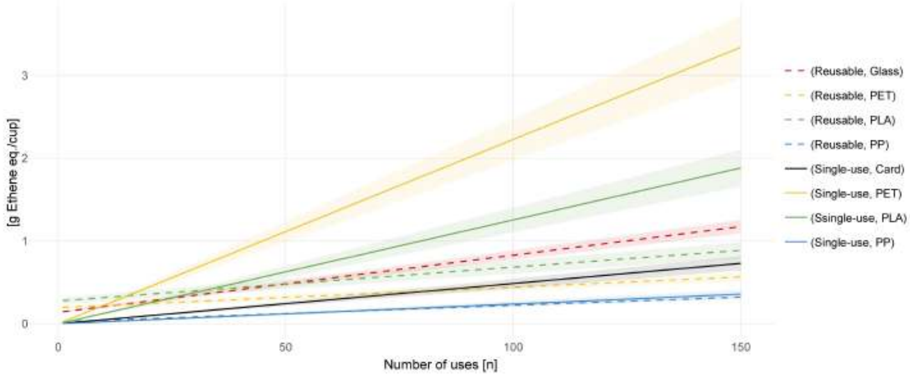
With respect to POC impact category (Fig. 8.3c) the best solutions for any n are the single-use and reusable PP cups. The PP reusable cups, in comparison with the PP single-use cups, achieve the BEP after about 50 uses. After 50 uses, the 2nd, 3rd and 4th best solutions for reusable cups are respectively the PET, PLA and glass cups, while for $n < 50$ the glass reusable cups perform better than the PLA reusable cups and for $n < 10$ they are even better than PET reusable cups. The PET reusable cup achieves the BEP for $n < 100$ with respect all single-use cup types (avoiding PP), while PLA and glass cups behave better than PLA and PET single-use cups (for $n > 30$). Finally, PLA reusable cups reach a BEP with respect to carboard+PE cup only after a very large number of



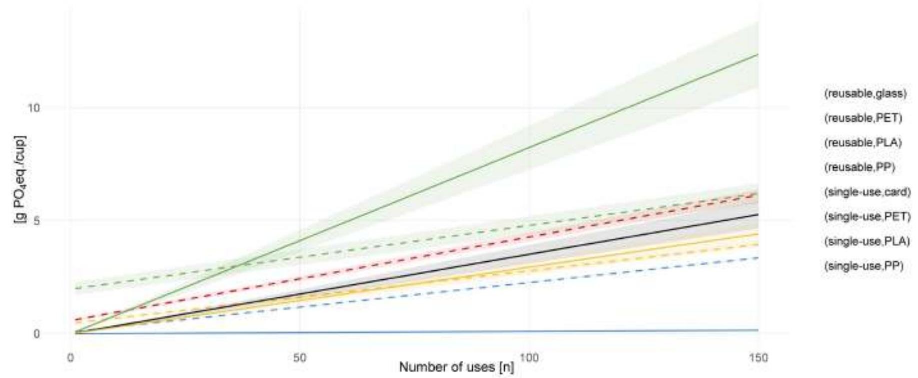
(a) Ozone Depletion (OD)



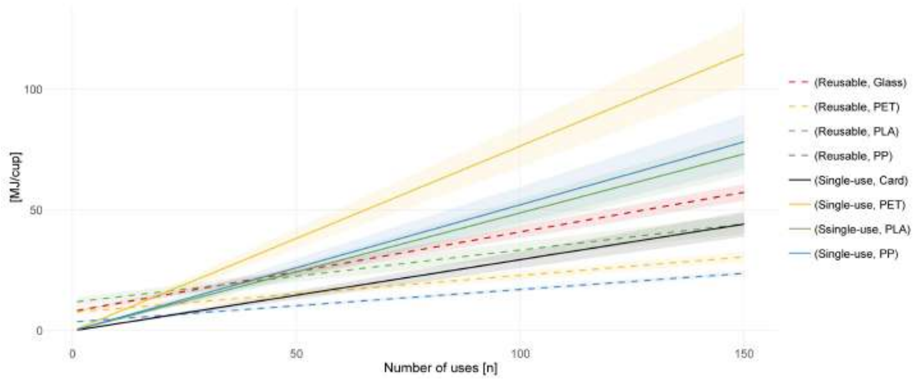
(b) Acidification (A)



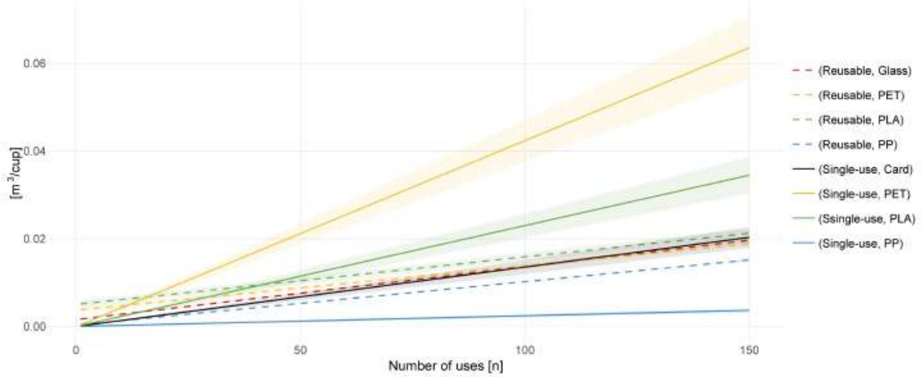
(c) Photochemical ozone creation (POC)



(d) Eutrophication (E)



(e) Non-Renewable Energy Use (NREU)



(f) Water Scarcity Indicator (WSI)

Figure 8.3: Reusable vs single-use cups impact categories. Scenarios for the seven analyzed midpoint impact categories with offsite washing with a transport distance of 20km during the use phase and energy recovery at EoL for plastic materials and recycling for glass.

reuses ($n > 350$).

In terms of eutrophication (E), Fig. 8.3d points out that single-use PP are always better than reusable cups for any number of reuses. Reusable PP and PET cups, with respect all single-use cups, reach a BEP respectively, after less than five uses, and around 60 uses. PLA is very impactful in terms of eutrophication impact category and it is the worst one, even if due to the difference in weight glass reusable cups perform better only for less than 150 reuses.

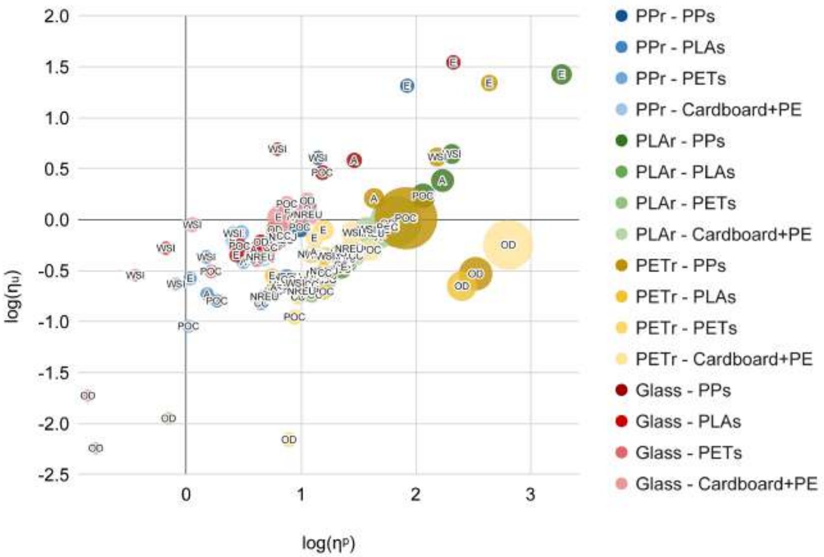
The behaviour of the NREU impact category (Fig. 8.3e) is similar to that of the CC impact category. Reusable plastic cups reach the BEP for $n < 50$ versus all types of single-use cups, with the only exception that the cardboard+PE cups perform slightly better than in the CC case.

Finally, according to Fig. 8.3f, the best solution for the WSI is the single-use PP cup which is always better than any other solution. With respect to reusable cups, the best cup material is again the PP, while the worst one is the PLA. All reusable cups achieve a BEP (avoiding the PP single-use cup) for $n < 50$ vs the PLA and PET single-use solution and for $n < 150$ vs the cardboard+PE cups.

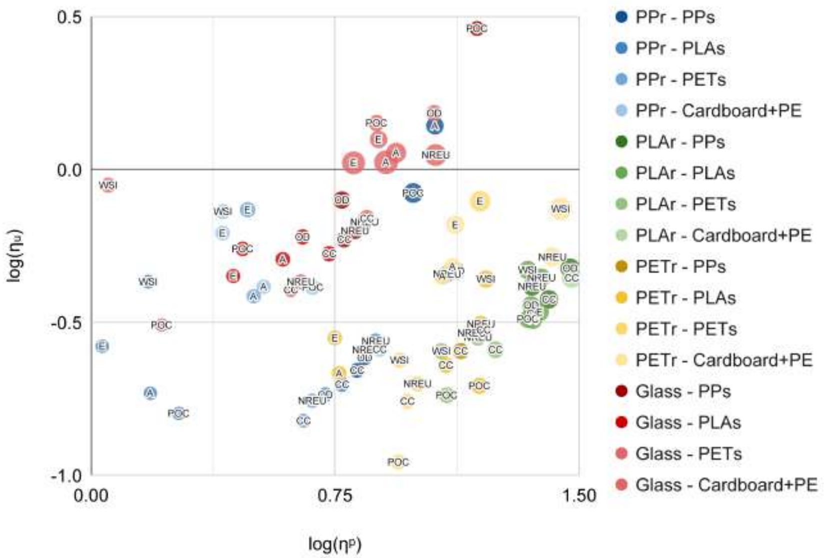
In conclusion, single-use PP cups are the best solution with respect to A, POC (for $n < 100$), E, and WSI, while reusable PP cups are the best ones among the other reusable solutions with respect all midpoint impact categories. PET and PLA reusable cups are, respectively, the 2nd and the 3rd best choice, among reusable cups except for the OD, E, and WSI impact categories. In fact, PET is the only material with a not negligible OD impact (i.e. it is the worst material), and, PLA, due to the impact during the production phase, is the worst solution with respect to E and WSI impact categories. Regarding single-use cups, the cardboard+PE cups are the best considering the CC and NREU impact categories, while, for all the other impact categories, the PP single-use cup solution performs better. For all categories, PLA and PET single-use solutions, generally, impact more than PP and cardboard+PE. On the contrary, reusable plastic (PP, PET, PLA) cups reach a BEP for all the impact categories (except for the above-mentioned cases against single-use PP cups) after a variable number of reuses, generally lower than 150. Finally, for all the impact categories, because of the high weight, the glass cups are strongly affected by the transport phase, and even if the production and EoL phases, in some cases, is better than reusable plastic cups, the impact for large n is always the worst. Thus, a more detailed analysis of transport distance is presented in the next paragraph.

Use and product efficiency: scatter plot

The material analysis are also reported in the scatter plots. Fig. 8.4b reports a zoom of the results in the range $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$. Different colours represents different materials for the reusable cups, while different gradients of the same colour point out the comparison of the same material for the reusable cups with the different materials for single-use cups. The size of each point is proportional to the BEP n for $\log(\eta_u) < 0$, while for $\log(\eta_u) > 0$ represents a negative n. The graph straightforwardly shows, for any case, if, and when, the BEP is achieved simultaneously for all analyzed impact categories. The reusable glass cups (red series) are the worst performing solution since many impact categories lie in the worst case quadrant ($\log(\eta_u), \log(\eta_p) > 0$) and $\log(\eta_u)$ is generally closer to 0 than the other materials. In terms of product efficiency,



(a) All data



(b) Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$

Figure 8.4: Scatter plot of use vs product efficiency (η_u vs η_p). Midpoint impact categories refer to offsite washing and energy recovery EoL strategy.

the PLA is the worst performing plastic material for reusable cups (green series) for almost all impact categories since $\log(\eta_p)$ is generally larger with respect to PP (blue series) and PET (yellow series) reusable cups. Regarding PET reusable cups, the large size of POC and OD points shows that the BEP is achieved only after a large number of reuses. This result is simply explained by Eq. 7.44; indeed, as $\eta_u \to 1$ (i.e. $B_{x,j} \to X$), or $\log(\eta_u) \to 0$, $n \to \pm\infty$. PP reusable cups are slightly better than PLA and PET reusable cups for the production and EoL phases. With respect to the use efficiency η_u, all three types of reusable plastic cups achieve a BEP, since points lie in the third and fourth quadrant ($\log(\eta_u) < 0$) for all impact categories except for A, POC, E, and WSI with respect to the PP single-use cups.

Use phases and transport distance analysis

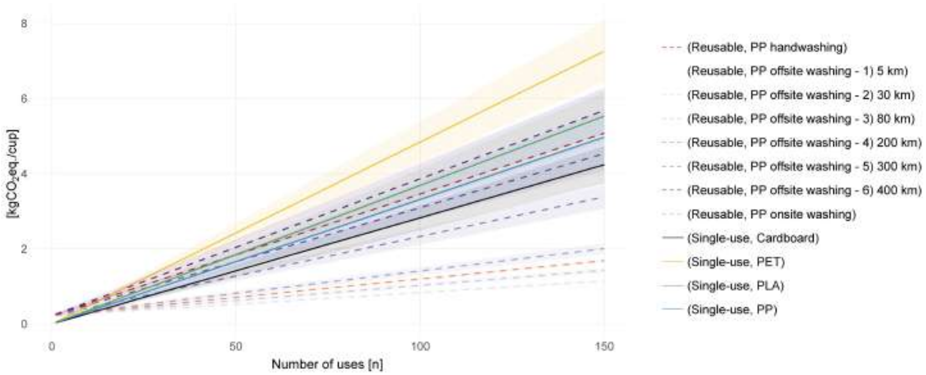


Figure 8.5: Climate Change impact categories for transport scenarios. CC of reusable PP cups for onsite handwashing/washing and offsite washing (dashed lines) VS single-use (continuous lines).

Since PP reusable cups, from the previous section analysis, perform better than the other reusable cups for almost all impact categories, in this section results and graphs are presented referred mainly to PP reusable cups and the average weights. Figure 8.5 shows the results for the CC impact category related to the PP reusable cups and the four types of single-use cups with respect to the three use scenarios. The plot highlights how, for the use phase, the best washing scenario is the *offsite washing* with a distance lower than 50km, then the *onsite washing*, subsequently the *offsite washing* with a distance lower than 350km, and, finally, the *handwashing* scenario. With a transport distance greater than 350km the *offsite washing* is always the worst scenario. In each scenario of the use phase: handwashing, dishwasher, and industrial dishwasher (for a distance of 10+10 km), the impacts are due, for a percentage higher than 75%, to the electricity consumed. The optimization of the system, achieved at an industrial level, allows to considerably reduce energy consumption and therefore limit impacts.

With respect to the single-use cups, the *onsite handwashing scenario* never achieves an environmental BEP, in terms of CC, vs the cardboard+PE and PP cups (although the line for onsite handwashing lies on the uncertainty shaded area of the PP cups) while the onsite washing scenario (or the offsite washing with equivalent CC impact) achieves the environmental BEP with a number of reuses lower than 20.

According to the area of interest classification, it emerges that local entities or institutions are necessary to manage the use phase. Indeed, for instance, CC impacts for the reusable plastic cups are lower than single-use cups if and only if distances are lower than 30-50km, thus, if a local entity in each City/Metropolitan Area is set up.

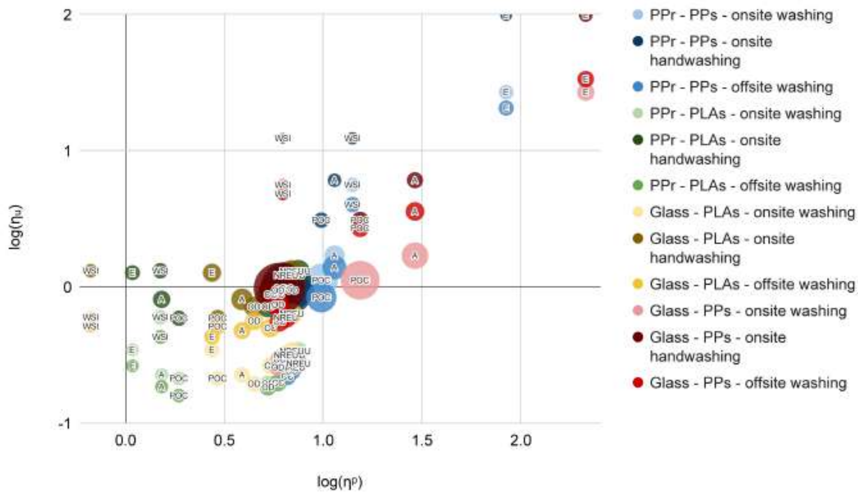
Table 8.3 points out how $n_{km,max}$ is negative, with respect to single-use PP cup, for Acidification, Eutrophication, and WSI midpoint impact categories.

Table 8.3: Maximum distance $[km]$ for the offsite washing scenarios. $n_{km,max}$ is the maximum number of allowed km for infinite number of reuse for which PP reusable cups are environmentally better of the four different single-use cups. The use phase does not depend on the material of the reusable cup but only on its weight.

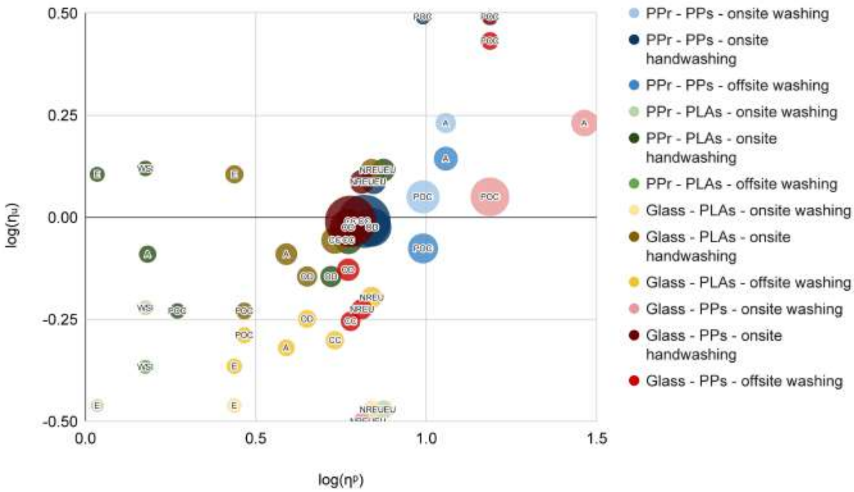
Maximum distance $n_{km,max}$ $[km]$ **for the use phase** for PP reusable cups				
Midpoint impact category	PP	PLA	PET	Cardboard
CC	357	406	556	293
OD	239	332	12217	100
A	-6	423	166	150
POC	33	364	681	113
E	-198	658	101	161
NREU	339	311	539	152
WSI	-528	986	2413	290

The negative numbers represent the case when the environmental BEP is not achieved either for an infinite number of reuses. Although a negative number does not represent a real situation, it is still a useful indicator. Indeed, when a negative number is close to zero (e.g. the case of A for PP cups) it means that with a slight improvement in the washing process for that impact category the environmental BEP can be achieved. Excluding the negative numbers, the minimum value of maximum allowed km occurs for the POC impact category in the case of PP single-use cups (33km). All the other values are greater than 100km, which means that, for an infinite number of reuses, if the distance during the use phase is lower than 100km an environmental BEP is always reached (excluding the impact categories above mentioned).

Finally, the same results can be obtained for the other reusable cups simply by multiplying the $n_{km,max}$ in Table 8.3 by a scaling factor due to the difference in weight between the cups. For instance, for glass cups the scaling factor, according to Table 8.1, is 0.11 (40/360 = 0.11) because of the glass cup weight (360gr) and the PP cup weight (40gr). Thus, the maximum number of allowed km for the glass reusable cups to achieve an environmental BEP, for all non-negative values in Table 8.3, is much lower, i.e. less than 15km.



(a) All data



(b) Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$

Figure 8.6: Scatter plot (logarithmic scale) with different use phases. Use efficiency η_u vs the product efficiency η_p. The acronyms CC, OD, A, POC, E, NREU, and WSI represent respectively: global warming, ozone depletion, acidification, photochemical oxidant creation, eutrophication, non renewable energy use, and, water scarcity indicator impact categories

Use phases and transport distance analysis

Finally, the best and the worst performing reusable cups, i.e. PP and glass cups, have been selected in order to analyze the different use phases. Results, in terms of use (η_u) and product efficiency (η_p) are plotted in Figure 8.6b with a zoom for the range $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$. Colors represent the comparison between a different couple of materials (e.g. reusable PP cups vs PLA single-use cups) while the color gradients highlight the different use phases for the same couple of materials.

Handwashing, as previously discussed, is the worst solution for all analyzed midpoint impact categories and the BEP in many cases is not reached. On the contrary, offsite washing for PP reusable cups is the best solution and the BEP is achieved with respect to PLA single-use cups for all impact categories. Comparing PP reusable and single-use cups, instead, the BEP is not achieved for A, E, and WSI. Reusable glass cups, again, are the worst-performing solution. The BEP is achieved, in terms of CC, OD, and NREU (vs PP single-use cups) and of CC, OD, A, POC, E, and NREU (vs PLA single-use cups).

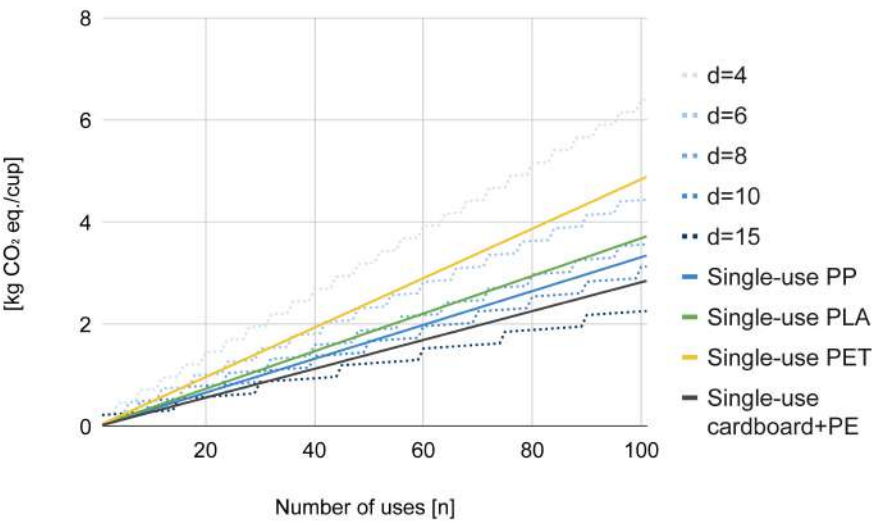


Figure 8.7: Dispersion rate in terms of CC impact category. Reusable PP cups for offsite washing (dotted lines) vs single-use (continuous lines) with different dispersion rate.

Dispersion Rate

Figure 8.7 shows the CC for reusable PP cups (dotted lines) vs single-use cups (continuous lines) with an increasing dispersion rate d. d is the average number of reuses before a reusable cup is dispersed and is substituted with a new one. Thus, after d uses, the production and EoL impacts of a new reusable cup are taken into account; in Figure 8.7 this effect corresponds to a “jump” in the impact. Previous studies analyzed these scenarios comparing different dispersion rates for reusable cups (Vercalsteren et al.,

2007) or for reusable plastic crates (Tua et al., 2019). Figure 8.7 shows how this is a "false" problem since the dispersion rate can be easily mapped into the environmental BEP n. Thus, for $d < n$ (see the case with $d = 4$ in Fig. 8.7) the environmental BEP is never reached, for $d \gg n$ (e.g. $d = 15$ in Fig. 8.7) once achieved the BEP the reusable cups are always better than the single-use cups, while for $d \sim n$ every time a reusable cup is dispersed into the environment the next usages of the reusable cup are environmentally worse up to the BEP is reached again (e.g. $d = 8$ in Fig. 8.7)

EoL scenarios: recycling vs energy recovering

In order to show the rationale of the proposed methodology the EoL environmental impact variations between the two EoL scenarios (recycling vs energy recovering) for PP and PET single-use and reusable products have been also evaluated. Precise results are reported in Table 8.4. For the PLA cups, composting has been considered instead of recycling. Recycling is always better than energy recovery for reusable cups, in terms of CC since $\Delta C_{Y_{0,1\to2}} < 0$, for any considered material (PP, PLA or PET). Moreover, recycling is better in terms of POC and NREU for PP reusable cups, while PLA composting is worse than energy recovery for all midpoint impact categories (excluding CC). Finally, PET recycling, for reusable cups, is better than energy recovery for all impact categories (excluding OD). On the contrary, for single-use cups, results have to be considered with the opposite meaning and when a negative sign occurs, i.e. $\Delta C_{X_{1\to2}} < 0$, both the product and the use phase efficiency are negatively affected.

Finally, Table 8.4b and 8.4c must be read simultaneously and quickly show when a change in EoL strategy for single-use products induces a change in the sign for n, and, thus, the environmental BEP is now reached or not.

By comparing recycling C_{X_2} with energy recovery C_{X_1} strategy for single-use in a few cases the BEP is no more achieved. In particular, in the case of onsite washing, with respect to CC for PP cups, the environmental BEP is no longer achieved when single-use cups are recycled instead of incinerated, while for PET single-use cups the BEP is no longer achieved for A, E, and WSI impact categories. With respect to PLA cups, instead, there is no change in the sign for any impact category for n by changing the EoL strategy for single-use. In the case of offsite washing, instead, there is only one change in sign (for Eutrophication for PP cups) but in this case it's a positive change in sign, thus, the BEP is now achieved. Again, for PLA there is no change in the sign for n, and for PET as well. Thus, by analyzing the two best use phase scenarios for reusable cups, i.e. onsite washing and offsite washing, in a scenario where single-use cups are 100% recycled the environmental benefits are no longer maintained even for the CC.

8.1.3 Discussion

By adopting this approach based on the environmental BEP, the product and use efficiency, a standard functional unit, i.e. one single-use, can be used, simplifying comparisons among LCA studies. Such an approach may be particularly suitable for monitoring the performance of an organization in the most recent framework of the Organizational LCA (OLCA) (Martínez-Blanco et al., 2015) but further studies are needed to homogenize results' interpretation according to UNEP (Blanco et al., 2015) guidelines and to the most recent ISO/TS 14072: 2014 (International Organization for Standardization, 2014).

Midpoint impact category		ΔC_Y			ΔC_X		
Acronym	**Unit of Measure**	**PP**	**PLA**	**PET**	**PP**	**PLA**	**PET**
CC	kg CO_2 eq./cup	-0.1420	-0.2433	-0.2674	-0.0249	-0.0118	-0.0344
OD	g CFC-11 eq./cup	$0.0660x10^{-4}$	$0.0821x10^{-4}$	$0.0081x10^{-4}$	$0.0116x10^{-4}$	$0.0040x10^{-4}$	$0.0010x10^{-4}$
A	g SO_2 eq./cup	0.00	0.3045	-0.4578	0.00	0.0148	-0.0589
POC	g Ethene eq./cup	-0.0052	0.0160	-0.0313	-0.0009	0.0008	-0.0040
E	g PO_4 eq./cup	0.1438	0.2415	-0.0091	0.0252	0.0117	-0.0012
NREU	MJ/cup	-1.8500	1.5365	-3.4957	-0.3238	0.0746	-0.4495
WSI	m^3/cup	$0.0023x10^{-2}$	$0.0315x10^{-2}$	$-0.2583x10^{-2}$	$0.0004x10^{-2}$	$0.0015x10^{-2}$	$-0.0332x10^{-2}$

(a) Variations in EoL environmental impact for reusable cups C_Y and single-use cups C_X. The comparison is between energy recovery and recycling (or composting for PLA). Negative values in ΔC_Y implies an improvement in the production efficiency, while negative values in ΔC_X implies a worsening of both the production efficiency and use phase efficiency.

Midpoint impact category		$\frac{(X_2-B_{Y_1})}{(X_1-B_{Y_1})}$ Onsite Washing			$\frac{(X_2-B_{Y_2})}{(X_1-B_{Y_2})}$ Offsite Washing		
Acronym	**Unit of Measure**	**PP**	**PLA**	**PET**	**PP**	**PLA**	**PET**
CC	kg CO_2 eq./cup	-0.063	0.564	0.111	0.141	0.688	0.242
OD	g CFC-11 eq./cup	1.405	1.098	1.001	1.336	1.072	1.001
A	g SO_2 eq./cup	1.000	1.103	-0.243	1.000	1.077	0.223
POC	g Ethene eq./cup	4.157	1.079	0.795	0.432	1.056	0.817
E	g PO_4 eq./cup	0.083	1.217	-0.203	-0.486	1.166	0.909
NREU	MJ/cup	0.093	1.231	0.251	0.258	1.154	0.356
WSI	m^3/cup	0.964	1.166	-0.162	0.941	1.105	0.001

(b) Quick Indicator to identify when the environmental break-even points n change sign. Negative values imply that a change in the sign for n occurred as a consequence of EoL scenario change for single-use products.

Midpoint impact category		$(X_2-B_{Y_1})$ Onsite Washing			$(X_2-B_{Y_2})$ Offsite Washing		
Acronym	**Unit of Measure**	**PP**	**PLA**	**PET**	**PP**	**PLA**	**PET**
CC	kg CO_2 eq./cup	-0.0053	0.0016	-0.0038	0.0003	0.0071	0.0017
OD	g CFC-11 eq./cup	$0.0019x10^{-3}$	$0.0014x10^{-3}$	$0.0714x10^{-3}$	$0.0024x10^{-3}$	$0.0020x10^{-3}$	$0.0720x10^{-3}$
A	g SO_2 eq./cup	-0.0292	0.0492	-0.0300	-0.0064	0.0719	-0.0072
POC	g Ethene eq./cup	-0.0019	0.0031	0.0053	-0.00001	0.0050	0.0072
E	g PO_4 eq./cup	-0.0139	0.0152	-0.0164	-0.0033	0.0257	-0.0059
NREU	MJ/cup	-0.0565	0.0815	-0.0296	0.0228	0.1608	0.0497
WSI	m^3/cup	$-0.1226x10^{-3}$	$-0.0343x10^{-3}$	$-0.0997x10^{-3}$	$-0.0781x10^{-3}$	$0.0102x10^{-3}$	$-0.0552x10^{-3}$

(c) When a change in sign of n occurs the difference $(X - B_Y)$ shows if the new EoL strategy moves from best/normal case ($n > 0$) to limit/worst case ($n < 0$) or viceversa. Negative sign of $(X - B_Y)$ represents negative values of n.

Table 8.4: EoL comparison between recycling and energy recovery

In next subsections, findings of the present work are compared with previous studies, highlighting and discussing limitations and advantages of the proposed methodology.

Comparison of results with literature

In the last decade, the comparison of environmental performance between reusable and disposable cups has been the subject of several studies. Studies often have shown the difficulty of completing an effective and objective comparison. For instance, Harst et al. (2013) compared ten disposable cups, showing that, due to the different methodological choices and differences in legislative rules, a reliable comparison was not feasible. A. Vercalsteren et al. (2010), instead, analyzed four types of cups - reusable polycarbonate and single-use polypropylene, PE-coated cardboard, and polylactide cups - in large and small events thanks to a comparative LCA study. To compare reusable versus single-use cups, they introduced the *trip rate*, i.e. the mean number of uses for a reusable cup. They concluded that none of the reusable cases is always better than single-use cups neither at small nor large events. Garrido et al. (2007) compared single-use and reusable cups for large events in Spain concluding that the minimum number of uses to have a smaller impact is 10. A similar result was also determined in the present study by referring to the global warming category, in fact for a number of reuses between 10 and 50 times all types of reusable cups show fewer impacts than single-use cups. Although Garrido et al. (2007) reported that reusable cups with respect to ozone layer depletion, heavy metals, and carcinogenic compounds, are always worse than single-use due to the impact during the washing phase. The comparison between reusable and single-use coffee cups - made of different materials - were performed in a work by J. Almeida et al. (2018). Polypropylene and glass reusable cups, produced by a specific company, were compared with generic PP and bamboo reusable cups and with paper and PLA single-use cups. From this study it emerges that PP and glass are the best materials for cups; in particular reusable cups - made of these materials - are better than disposable alternatives after around 10-20 uses. These results are partially in agreement with what we obtained from our analysis. The main difference is represented by the result of the glass cups in fact in the work of J. Almeida et al. the cups weight does not affect the impacts of the use phase because the study hypothesizes that the cups are used and washed in a home context (therefore without the need of any kind of transport). In another work, Potting and Harst (2015) compared three disposable cups - polystyrene, biobased, and compostable polylactic acid (PLA) and bio-paper - with polystyrene reusable cups (hand-washed or dish-washed). Again, no overall preference was possible neither among the different disposable cups nor among the disposable ones and the reusable cups. More precisely, reusable cups with dishwashing (4 uses before to wash a cup) are worse than disposable polystyrene cups for four midpoint impact categories - terrestrial ecotoxicity, ozone layer depletion, human toxicity, marine aquatic ecotoxicity - out of the eleven considered impact categories, while, with handwashing, all impact categories are worse.

In recent years, to facilitate comparison between single-use and reusable products, the European Commission reported a thorough "life cycle inventories of single-use plastic products and their alternatives" (Paspaldzhiev et al., 2018) for single-use plastics products (e.g. cigarette butts, drinks bottles, cutlery, straws, food containers, drinks cups, ..), with suggestions about some non-plastic reusable alternatives. From the report, it emerged that washing impacts are strongly affected by the technology used and by ecodesign criteria but the report does not provide results in terms of the number of usages. The effect on the final impacts of the technology used to model the system in the use phase emerges from the comparison with the recent work by Changwichan et al. (2020); as reported in this study, the impacts generated by handwashing are considerably lower than those obtained when using a dishwasher. In their work both handwashing and dishwashing use room temperature water and a few grams of detergent (5g and 4g respectively). With these hypotheses, dishwashing uses less water but more electricity which causes higher environmental impacts due to its production. Other aspects to keep in mind - when examining similar works - concern the geographical region and the technology used to model the production phase of the cups. In fact, Changwichan et al. (2020) suggest how reusable steel cups show better environmental performance than PP, PET and PLA single use cups, for different impact categories. Thus, results from previous works show that they are all closely linked to the specific situation and the assumptions examined.

Table 8.5: Strategies to improve the reusable products impact.

Cases	**Use efficiency**	**Product efficiency**	**BEP**	**Strategy**
Best Case	$0 < \eta_u < 1$	$0 < \eta_p < 1$	$n > 0$	1) Improve the use phase if $n \gg 1$
Normal Case	$0 < \eta_u < 1$	$\eta_p > 1$	$n > 0$	1) Improve the use phase if $n \gg 1$ 2) Improve reusable product production or change material for reusable product
Limit Case	$\eta_u > 1$	$0 < \eta_p < 1$	$n < 0$	1) Improve the use phase to reach a BEP
Worst Case	$\eta_u > 1$	$\eta_p > 1$	$n < 0$	1) Improve the use phase to reach a BEP 2) Improve reusable product production or change material for reusable product

Limitations and advantages

Recently, within a report of the Italian Circular Economy Stakeholder Platform (ICESP), an interdisciplinary working group composed by researchers, practitioners, and policy-makers in Italy, LCA methodology has been recognized as one of the three fundamental categories (together with specific circularity indicators and Corporate strategy indicators) to assess circularity (especially relevant to the plastics industry) in order to have a systemic and holistic overview of the impacts generated by certain products (ICESP, 2020a). Despite within the report the need of applying and adopting LCA methodology is pointed out, no clear and precise methodology is described in order to evaluate neither circular products nor to compare different business models (e.g. single-use vs reusable). Moreover, it is clearly stated how, actually, LCA methodology needs experts, and the choice of the functional unit, the boundaries of the system can strongly affect the findings undermining the comparison and the generalization of the results. Hence, the methodology here proposed may support and facilitate comparisons among different business models. Although results obtained from this study also depend on specific assumptions and boundary conditions due to the system itself, the proposed approach may facilitate the phase of interpretation of results in LCA analyses. In particular, the introduction of the environmental BEP n allows to easily analyze close-loop scenarios, by maintaining a simple functional unit (i.e. serving 0.4 liters of draught beverages in one go) instead of more complex ones (e.g. hundreds of uses). Moreover, by studying the environmental impacts in terms of the proposed KPIs, i.e. the environmental BEP n, the use phase efficiency η_u and the product phase efficiency η_p, it is possible to decouple the effects of a variation in the production phase, or in the use phase, of a reusable product. Indeed, a variation on the use phase may affect the achievement, or not, of an environmental BEP for a reusable product, while a variation on the production and EoL phases of the reusable product only affects when the BEP is achieved (i.e. the minimum number of reuses). Thus, depending on the values of η_u and η_p, possible strategies (Table 8.5) may be easily identified, to improve the efficiency of a reusable product and to achieve an environmental benefit with a reasonable number of reuses.

On the contrary, a few limitations emerged. First, the environmental BEP assessment allows the simultaneous comparison of different midpoint impact categories, since the two KPIs for the use and product efficiency are dimensionless by definition, but the usual midpoint impact category weighting process towards common endpoints still remains a challenge. Second, the results obtained for the use phase are strongly affected by electricity consumption. Indeed, more than 75% of the impact is due to energy consumption. Further investigations are needed to evaluate differences in assumptions for the electricity mix (e.g. 100% renewable energy) or for the soap and detergent composition, such as the detailed study conducted by Tua et al. (2019) on reusable plastic crates. Third, the discussed EoL scenario needs an ad-hoc analysis with primary data from specific companies and plants to evaluate uncertainties and the results' accuracy. Furthermore, EoL implications have to be further investigated in order to simplify the analysis of the effects both on the product and the use efficiency, when different single-use product EoL processes have to be compared. Fourth, in this study an uncertainty analysis on the cup weight is discussed, by presenting the effects of a variation of weight with respect to an average value. Although this assumption represents the most common cup weight found in European marketplace, further investigations are needed to cover the high variability in weight. Indeed, by varying the weight, the material ranking, i.e. best or worst performing cups, may change significantly. Thus, a full market analysis should be necessary in order to identify the best solution for reusable or single-use cups and to define boundary assumptions (e.g. weight). Finally, due to lack of primary data for the whole supply chain, this study relies on secondary data obtained from the literature; thus, for future studies specific analyses on production, use or EoL processes may be needed to improve obtained results.

Simultaneous variation of EoL scenario of single-use and reusable products.

If one wants to compare different EoL scenarios for both single-use and reusable products a more complex case arises for the product efficiency η_p. Indeed, by defining $\eta_{p,1} = \frac{Y_1}{X_1}$ and $\eta_{p,2} = \frac{Y_2}{X_2}$, the variation in the product efficiency depends on a mixed comparison of impacts of reusable and single-use products, according to

$$\Delta\eta_{p,1\rightarrow 2} = \frac{X_1 Y_2 - Y_1 X_2}{X_1 X_2}. \tag{8.5}$$

Since $X_1, X_2 > 0$ by hypothesis, Eq. 8.5 means that

$$\Delta\eta_{p,1\rightarrow 2} > 0 \Rightarrow \frac{X_1}{X_2} > \frac{Y_1}{Y_2}, \tag{8.6}$$

and a full analysis is necessary to understand the impact of the variations of the EoL scenarios. On the contrary, the use phase efficiency and thus the sign of the environmental BEP still depends only on EoL impact for single-use product C_X.

8.1.4 Conclusion

The present study introduced a novel methodology for the interpretations of results from comparative LCA analyses in order to evaluate reusable versus single-use products. The methodology lies on three main KPIs: 1) the *product phase efficiency* (η_p), 2) the *use phase efficiency* (η_u), and 3) the *environmental break-even point* (n). n represents the minimum number a reusable product has to be used in order to become environmentally better than an equivalent number of uses of a single-use product.

Four single-use cups (PP, PLA, PET, and Cardboard+PE coat) have been compared with four reusable cups (PP, PLA, PET, and glass) with respect to seven midpoint impact categories - Climate Change (CC), Ozone Depletion (OD), Acidification (A), Photochemical Oxidant Creation (POC), Eutrophication (E), Water Scarcity Indicator (WSI) and Non-Renewable Energy Use (NREU) - taking into account two EoL strategies (energy recovery and recycling) and three use phase strategies for reusable cups (onsite handwashing, onsite washing and offsite washing). Composting, instead of recycling, has been considered for PLA.

Considering the offsite washing phase - i.e. transport distance of 20km and industrial washing machines - and the energy recovery EoL phase, the results highlight that reusable plastic (PP, PET, PLA) cups reach a break-even point for CC and NREU for $n < 150$, with respect to all analyzed single-use cups. On the contrary, in terms of A, E, and WSI, single-use PP cups are the best option. Reusable glass cups are worse than any other solution due to transport during the use phase. Generally, reusable cups midpoint impact categories are strongly affected by the distance during the use phase. A limit result has been quantified in terms of the maximum distance (km) allowed during the use phase in order to achieve an environmental break-even point after an infinite number of reuses. With respect to PP single-use cup, the environmental break-even point is never achieved for A, E, and WSI, while for PET, PLA, and cardboard single-use cup the environmental break-even point is attained for all midpoint impact categories. Excluding also POC impact category with respect to PP single-use cups, in all the other cases a break-even point is achieved for a transport distance during the use phase lower than 100km. Finally, onsite handwashing is the worst solution while onsite washing is an intermediate solution. For instance, in terms of CC, they are comparable with offsite washing with a distance of 350km and 50km, respectively.

By considering recycling as EoL scenario the impacts are lower both for reusable and single-use products, while they are worse for composting (for PLA). Thus, considering single-use cups recycling, the break-even points are negatively affected. Indeed, when single-use cups are recycled and reusable cups are energy recovered, for the onsite washing, the break-even point is no more achieved either for CC for PP cups and for A, E, and WSI for PET cups, while for the offsite washing with 20km transport distance no noteworthy differences emerged.

Within the current transition to the circular economy, the presented methodology may be adopted by manufacturers of reusable products, as well as by researchers, practitioners, and decision-makers, to evaluate the introduction of new circular products, or circular business models, and to correctly identify if, and under which conditions, a reusable product is environmentally better than an equivalent single-use product. Future studies related on the discussed case study on reusable and single-use cups should focus on the comparison of different End of Life scenarios and in collecting up to date primary data related to the production and End of Life phase. More in general, the proposed methodology should be homogenized with the most recent framework of the Organizational Life Cycle Assessment introduced by the ISO/TS 14072:2014.

8.2 Circularity Indicator & MCDA

This section presents an application of a novel circularity indicator for the built environment, starting from the basic concepts of the built environment and the existing Building Assessment Certificate (an example of multi criteria decision analysis) and highlighting the pros and cons of current methodologies and applications. The text of this section is largely based on and adapted from the report *Benchmarking on circularity and its potentials on the demo sites* (Dario Cottafava, Ritzen, and Oorschot, 2020) and from the paper "Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects" (Dario Cottafava and Ritzen, 2021).

8.2.1 Basic Principles

To enable a circular and regenerative approach for the built environment, the first necessary step is to "take a picture" of the current situation of existing buildings in order to understand the in-use material, their environmental impact such as the Embodied Energy and Carbon. Thus, the request for the Material Passport, i.e. the complete list of materials used in a product/building, in the built environment has been largely spread as a compulsory approach for new buildings, as well as for renovation interventions (Heisel et al., 2020). Innovative tools and online platforms have been developed in the past decades in order to facilitate the data collection process and to allow decision-makers to quickly access useful information related to the materials stocked into existing buildings. For instance, Heisel et al. (2020) described the functionality of the Madaster platform by assessing the circularity of a new residential building unit UMAR in Stuttgart. Madaster (Madaster, 2018) is based on the Building Circularity Indicator (Verberne, 2016) and the Material Circularity Indicator (EMF, 2015) developed by the Ellen MacArthur Foundation.

Recently, the EU funded BAMB project (Buildings As Material Banks), in collaboration among 15 parties throughout Europe, developed an online platform to enable circular solutions in the built environment. Within the BAMB project (BAMB, 2020), a circular building assessment prototype has been developed as a beta version software that, from a BIM/CAD model, is able to combine BAMB generated datasets and other external/user supplied data and to provide an assessment of the reuse potential based on design decisions and material selection criteria. The Dutch Cirdax online platform (CIRDAX, 2020) provides a similar service. Starting from the material passport they offer a thorough management online dashboard that gives an overview of all the in-use materials with additional information such as pictures, embodied energy and carbon of materials. Both the described platforms and companies, currently, focus their business model on the circular assessment of buildings and on the data management and visualization of the bill of materials. Both of them evaluate the potentially recoverable materials and components through an ad-hoc reclamation audit conducted by experts.

Reclamation audit

A reclamation audit is a process to assess the reuse, recycling or remanufacturing potential of the materials used in a building. The main aim is to highlight which products and components may be reclaimed instead of being disposed into landfill or for energy recovery. Basically, the output of a reclamation audit is an inventory of materials containing, at least, 1) enough information related to products' characteristic (quality, amount, type, ...) and 2) optional and additional insights on possible destinations, technical characteristics and tips for disassembly and removal process. Such an inventory allows the owner, the involved architects or any other responsible stakeholder for the demolition/renovation process to indicate to a demolition/renovation contractors/subcontractors which components or products must be carefully dismantled and to provide them the necessary disassembly information. Moreover, third parties, material or second-hand markets can be informed or involved in the selling process. Currently, a recognized and standardized protocol does not exist. Typically, reclamation audits are conducted by experts who identify reusable / recyclable components and materials according to their previous knowledge and background. Figure 8.8 shows a simplified representation of a reclamation audit and the possible path for components, products and materials during a renovation / demolition process of a building. Even if a protocol does not exist yet and there is no consensus on the proper approach, several Design for Disassembly (DfD) criteria are largely adopted by practitioners and experts. Indeed, thanks to a successful Reclamation Audit several information may be obtained. One of the preliminary analysis, for instance, is to quantify the embodied energy and carbon of the materials, predict the impact/benefit on the embodied energy, or on other environmental aspects, when a particular component is recycled, reused or disposed.

Generally, a reclamation audit can be conducted by the building owners, consultants (architects, engineers), reuse/circular economy experts, reclamation dealers or construction/demolition contractors. Wassink (2016) analyzed and presented in a preliminary study the average percentage of identified components and products of a building with a recycling/reusing potential according to the opinion of different construction stakeholders. From the study emerged that the recoverable material percentage is strongly

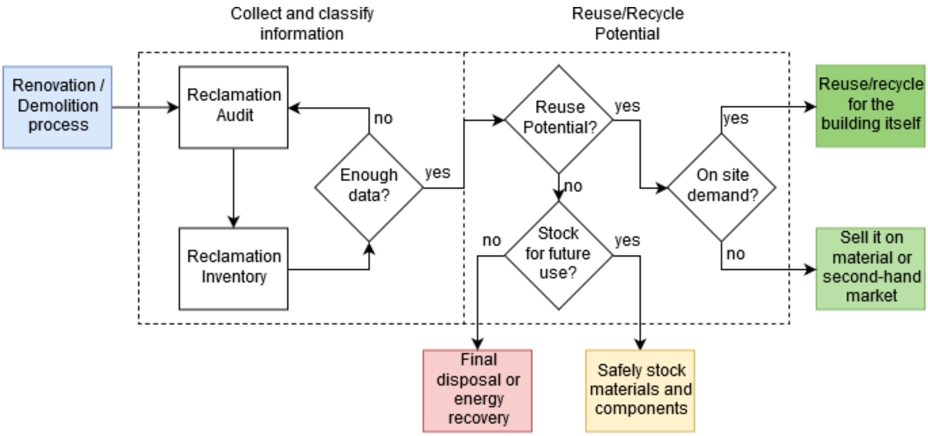


Figure 8.8: Reclamation audit representation. There are different possible paths depending on the recovering potential of materials and components.

affected by the skill and the background of the interviewed stakeholder. Indeed, the so-called salvage dealer, i.e. experts specialized in reclamation audit, identified as potentially recoverable more than 70% of components, while the owner only around the 5%. In-between, external consultants, general contractors and demolition contractors stated that, respectively, the 60%, the 30% and the 20% of components had a recovering potential. It is straightforward that a reclamation audit, in order to be successful, has to be conducted by expert stakeholders such as consultants (architects/engineers) or a dedicated salvage dealer. It seems, nowadays, that other stakeholders as the general or demolition contractors, as well as the owners, have not yet the skill, or they have no interest in identifying components for a potential recycling/reuse subsequent step.

On top of these results, one can ask: what defines a material or a single component that is potentially recyclable or reusable? Which are the features/characteristics to identify it? A preliminary list, not exhaustive, of the main aspects which affect the feasibility to close the material loop could include: the easiness of dismantling/disassembly, the existence of a demand, some intrinsic qualities (aesthetic, technical, ...), good condition and high quality, the price of the new equipment and of the logistic.

Buildings' Layers

Buildings are complex and living entities. To assess the circularity level of a building, like its environmental impact, some preliminary concepts are necessary. In particular, the components, sub-components and materials in a building are generally grouped into the so-called Brand layers (Brand, 1995), i.e. seven subsequent layers which differ in functions and lifespan. The seven layers are: 1) *site*, i.e. the ground where a building is built on, 2) *structure*, the main walls and load-bearing beams, 3) *skin*, the external walls and the roof, 4) *services*, e.g. pipes and sanitary services, 5) *space plan*, the internal wall and staircases, 6) *stuff*, furnishment and interior design and 7) *souls*, i.e. the people living with the building itself. Table 8.6 summarizes the seven layers as described by

Stankovic et al. (2015) and their average lifespan, where in this case the space plan is simply intended as interior design and not the wall itself. These considerations are of fundamental importance for a circularity assessment as each layer should not to affect higher, or lower, order levels as they differ in lifespan.

Table 8.6: Building layers and lifespan. Adapted from Stankovic et al. (2015)

Shearing layer	**Lifespan/Activity**
Site	Permanent
Structure	30-300 yr
Skin	20+ yr
Services	7-20 yr
Space Plan	3 yr
Stuff	< 3yr
Souls	Daily

Embodied Energy

Globally speaking, buildings consume nearly 40% of the total annual energy consumption during their life cycle (Manish K Dixit et al., 2013). Life cycle energy of a building includes Embodied Energy (EE) and Operational Energy (OE). The former refers to the amount of energy used during the construction, maintenance and demolition of a building (Azari et al., 2018), while the latter refers to the amount of energy needed for running Heating, Ventilation and Air Conditioning (HVAC) systems, the lighting and electrical and electronic equipment during the entire life cycle of the building (Ramesh et al., 2010). Over the life cycle, OE constitutes the higher percentage of energy consumption of a building (Raymond J Cole et al., 1996); this has collateral environmental impact. To lower this impact, the European Parliament instituted the nearly Zero Energy Building (nZEB): all new buildings and all new public buildings must be designed as nZEB by the end of 2020 and 2018, respectively (EP, 2010). Consequently, EE is becoming the most important part of energy use during the entire life cycle of a building as shown in Figure 8.9. EE has been defined in several ways, depending on the system considered. For instance, P. Crowther (1999) stated *"the total energy required in the creation of a building including the direct energy used in the construction and assembly process, and the indirect energy that is required to manufacture the materials and components of the building"*. Ding (2004) defined EE as *"the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building"*; thus, he also included the demolition phase. Concluding, EE can be split into:

1. Initial Embodied Energy (IEE), i.e. the energy required to extract raw materials, process them into products, transport the components and, finally, construct the building;
2. Recurrent EE (REE), the energy used to maintain the building during its useful

life;

3. Demolition EE (DEE), the energy to dispose, recycle, re-use any building part after the useful life of the building comes to an end.

Despite the significant efforts of the academic community and of practitioners to investigate the EE of buildings, several parameters - system boundaries, age of data, data availability, temporal, spatial and technological features (Manish Kumar Dixit et al., 2010) - affect building life cycle analyses. Moreover, such parameters are open to interpretation and debate, due to a lack of standard protocols which allow a comparability among studies. Indeed, the EE of residential buildings, on average, is $(5.51 \pm 1.56)\, GJ/m^2$, while for commercial buildings the average is slightly higher, i.e. $9.19 GJ/m^2$, but with a very large standard deviation of $5.4 GJ/m^2$. More precisely, Castro et al. (2019) identified the contribution of the main building layers in terms of Embodied Carbon, i.e. *Structure*, *Skin* and *Space Plan*, to be respectively 58%, 23% and 18% of the total.

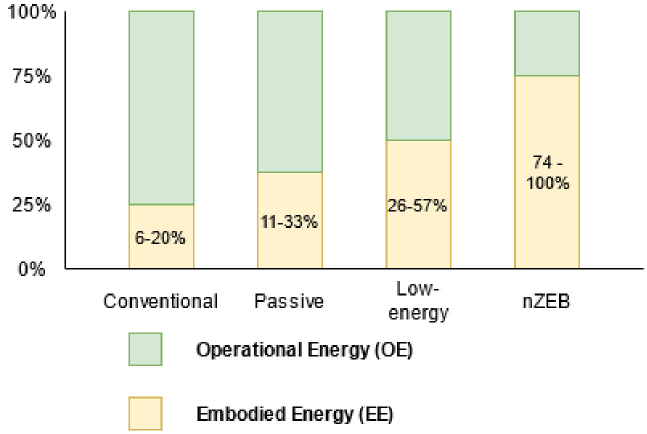


Figure 8.9: Embodied and Operational energy. Comparison among conventional, passive and near Zero Energy Buildings. Adapted from Azari et al. (2018)

In general, the ISO for Life Cycle Assessment (LCA) provides useful guidelines, which many research projects take into account, but it does not clarify on issues such as the quality of data or the system boundary to be adopted (Reap, Roman, et al., 2008). Moreover, the LCA analysis has a few limitations, especially when applied to existing buildings in different countries and regions. First, results computed by an LCA analysis are hardly generalizable due to specific geographical datasets. Second, if it is feasible to assess recent products/services thanks to up-to-date datasets, assessing an existing old building can be a very hard - if not impossible - task due to lack of data on used materials, their origin and their traceability. Results from such an assessment could be meaningless due to too many assumptions. Third, while an LCA of a simple product may be feasible, in time and complexity, an LCA for a complex building could be a challenging and very time-consuming task for practitioners. The application of an LCA, as a best practice, may slow down environmental assessment due to time-constraints of practitioners, as well as lack of expertise. Finally, to obtain a few final scores for decision-makers, a weighting process is a necessary step, and the overabundance of environmental indicators may affect the decision process by reducing its efficiency. Moreover, weighting processes are highly criticized in the academic community (Bengtsson et al., 2000), and they are not even recommended by the ISO standard.

These issues could be overcome in the design phase of new buildings, thanks to plugins and addons for common 2D and 3D modelling software, but not for existing old buildings. For instance, Naboni (2019) suggested the use of the plugin Grasshopper and LadyBug for Rhinoceros 3D. Ladybug Tools is a thorough collection of open source software to support environmental design, linking 3D CAD with validated simulation engines. Forth (2019) described pros and cons for semi-automated processes, from Building Information Modeling (BIM) to LCA. BIM programs can determine the surfaces and masses of used materials automatically. By linking a plugin such as Autodesk Dynamo, with LCA data, to a BIM model, a preliminary assessment of the environmental impacts can be achieved. Dalla Mora et al. (2019) discussed the advantages and disadvantages of using Tally and One Click LCA, two plugins for Revit. The Tally plugin, which uses the Gabi database, allows for a comparison among different designs. One Click LCA, on the other hand, can be used to obtain building certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM), the Leadership in Energy and Environmental Design (LEED), and Environmental Product Declarations (EPD).

8.2.2 Building Assessment Certificate

Nowadays, there exist dozens of certification schemes for the built environment all around the world. Almost each country developed its own certificate process with slight variations from one scheme to another. W. Lee (2013) presented a comprehensive review of earlier assessment certificates of the most known and worldwide adopted certificates: the Building Research Establishment Environmental Assessment Method (BREEAM) from UK, the Leadership in Energy and Environmental Design (LEED) from USA, the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) from Japan, BeamPlus from Hong Kong and the National Evaluation Standard for Green Building (ESGB) from China. Many others exist, such as the Australian GreenStar, the Canadian BEPAC (Building Environmental Performance Assessment Criteria), the European EMAS (Eco-Management and Audit Scheme) and so on, but they are based on the same general assessment approach, smoothly varying some criteria. Generally, the building assessment certificates are based on two or more levels of criteria. Each criterion is evaluated through qualitative, or quantitative, questions; then, many criteria are aggregated into macro categories by weighting each answer. For instance, the BREEAM scheme was composed by three levels: 10 issues, 69 categories and 114 criteria. It includes issues such as: management (22), health & wellbeing (14), energy (30), transport (9), water (9), materials (12), waste (7), land use & ecology (12), pollution (13), innovation (10). The numbers between the parentheses represent the maximum obtainable score for each issue, i.e. by normalizing the score over the total possible score, it represents the weight for each single issue. LEED scheme, instead, is based on a two-level system, categories and points. There are seven main categories: sustainable sites (26), water efficiency (10), energy & atmosphere (35), materials & resources (14), Indoor Environmental Quality (IEQ) (15), innovation in design (6) and regional priority (4). Finally, to each macro criteria, a maximum score is assigned in order to obtain a total ranking score for the assessed building. Depending on the obtained score, a final evaluation is given to the analysed building. For instance, the LEED scheme has a minimum score of 40-49 out of 110 to obtain the certificate, while the silver ranking is assigned for a total score of 50-59, the gold one for 60-79 and the platinum evaluation for a score greater than 80. Recently, there has been debate on how to advance the Building Assessment Certificate in order to include Circularity criteria. For instance, in *"A framework for circular buildings"* (K. F. Ben et al., 2018), the DGBC (the Dutch Green Building Council), in collaboration with other private and public partners (Circle Economy, Metabolic, SGS Search, Redevo Foundation) proposed new indicators to include circular economy criteria into the BREEAM scheme. Starting from seven general strategies for the Circular Economy, four main strategies for Circular Building have been identified:

1. reduce, to mitigate impacts the best strategy is to avoid new production;
2. synergise, once resource demands have been minimized, the second strategy is identifying local synergies;
3. supply, the remaining resource demands must be provided by adopting clean, renewable and recycled resources;
4. manage, information and data transparency are necessary for an efficient system.

The four Circular strategies have been applied to the main impact area - Materials, Energy, Water, Biodiversity and Ecosystem, Human Culture and Society, Health and Wellbeing, Multiple Forms of Value – identifying new, or modified, indicators for the BREEAM scheme. Finally, in 2020 the European Union launched an assessment framework, i.e. the *Level(s) Common Framework*, to measure circularity and sustainability in buildings based on six different Macro-objectives and a 16 Core Indicators (EC, 2020d). The six proposed areas[1] include GHG emissions and embodied impacts, design for disassembly, reuse and recycling criteria, water consumption, indoor comfort of households till resilience and adaptation to extreme weather risks. Each area consists of a few indicators and can, and should, be applied to any level/stage of the buildings (Conceptual design; Detailed design and construction; As-built and in-use). With respect other building assessment certificate, in this case, there is not a weighting step in the process, and the procedure needs a full LCA analysis.

To wrap up, the most common building assessment certificates evaluate hundreds of different criteria including social, environmental and economic aspects. Generally, they are based on a qualitative assessment such as the one shown in Figure 8.10 proposed by the DGBC as integration of the BREEAM scheme. Many criteria are self-declared by the certifier or the consultant in charge of the certification process. Optionally, a full LCA analysis can be provided by the certifier (it only gives additional scores on the final

[1] 1. Greenhouse gas emissions along a buildings life cycle; 2. Resource efficient and circular material life cycles; 3. Efficient use of water resources; 4. Healthy and comfortable spaces; 5. Adaption and resilience to climate change; 6. Optimised life cycle cost and value

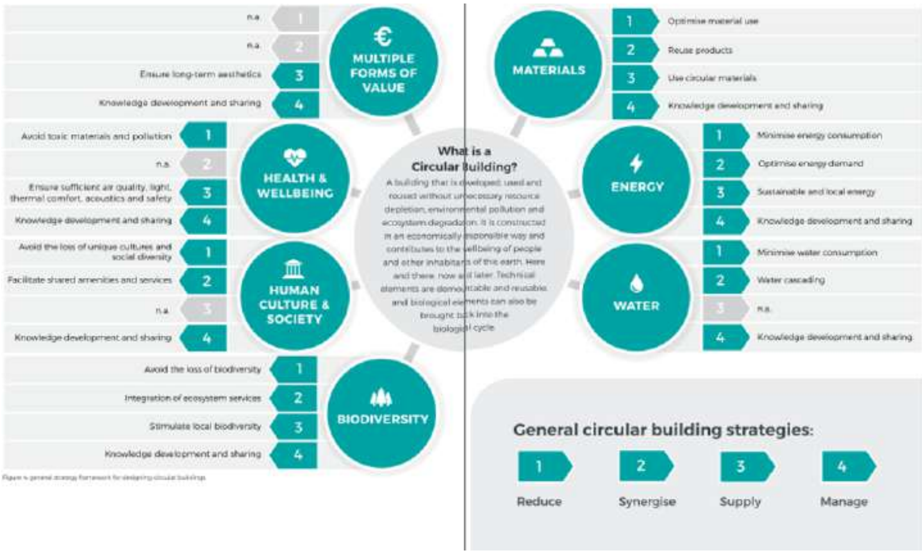


Figure 8.10: Circular building assessment example. New criteria proposed by the Dutch Green Building Council to integrate the BREEAM scheme. Source: K. F. Ben et al. (2018)

ranking). The main advantage of the building assessment certificate is to guarantee a standardized evaluation process worldwide for the built environment, especially useful for the decision-makers. On the contrary, they have many limitations from a rigorous scientific point of view. Indeed, first, they are affected by the same limitation of MCDA, i.e. the weighting process, and they can be influenced by the subjectivity of the certifier. In addition, they roughly sum criteria related to completely different aspects without any strong and robust methodology. Despite the criticisms, they still remain a useful tool for practitioners in order to quickly evaluate the environmental "level" of a building, to communicate to the owners, the tenants or other relevant stakeholders and to roughly benchmark different buildings for decision-makers.

8.2.3 A Circularity Indicator for the Built Environment

The Built Environment (BE) is responsible for more than 25% of all waste generated (Ellen MacArthur Foundation, 2015b) and most of the Construction and Demolition Waste (CDW) are downcycled (Chunbo Zhang et al., 2020). The consumption of raw materials and its collateral environmental impact highlights the need to adopt circular practices.

To indicate the level of circularity, a large number of indicators are employed. These Circularity Indicators (CI), such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (EMF), mainly focus on three aspects (EMF, 2015):

1. the amount of used virgin materials;
2. the amount of unrecoverable waste; and

3. the lifetime of the products.

However, a holistic methodology covering the circular assessment on the macro (material impact), meso (supply chain) and micro (design) level still needs to be fully developed (Verberne, 2016). To overcome these gaps, this research focuses on two main research questions:

1. How to improve the environmental assessment of the raw materials used in a Building Circularity Indicator?
2. How to quantify the End of Life potential of materials and building components worth recovering by adopting Design for Disassembly (DfD) criteria?

To bridge the gap between embodied aspects and design aspects, in this research, the Material Circularity Indicator (EMF, 2015) is combined with Embodied Energy (EE), Embodied CO_2 (EC) analyses (Ramesh et al., 2010) and Design for Deconstruction criteria (Akinade et al., 2017) in two indicators: the Building Circularity Indicator (BCI) and the new proposed Predictive BCI (PBCI). Both indicators are presented in a *Full* and *Simplified* version. The two indicators were tested on 8 demonstrators in different climate zones in the EU. On a macro level, the environmental impact assessment is implemented by evaluating the EE and EC, instead of only the mass of the used materials. At the micro level, the relationship between environmental impacts and design criteria, typically provided simply as DfD guidelines, is established. At the meso level, a precise methodology to facilitate the decision of which parts of a product can be really recycled or reused is provided.

The rest of the section is structured as follows. In section 8.2.4, the new proposed methodology is introduced to further advance the BCI linking DfD criteria and EE and EC analysis. In section 8.2.5, results for the 8 demonstrators, in terms of embodied aspects, recovering potential and BCI, are analyzed. Finally, in section 8.2.6, concluding remarks and further improvements are pointed out.

8.2.4 Methodology

This research follows a multiple case study (Yin, 2018), done purposefully (Stake, 1995) by selecting eight relevant information-rich demonstrators all around Europe to provide an analytical generalization of the findings (R. Johansson, 2007) for similar buildings. Quantitative and qualitative data have been used as data sources. A concurrent mixed-method was used, giving more emphasis to quantitative rather than qualitative data (R. B. Johnson et al., 2004). Primary data have been collected from experts for each demonstrator directly through:

1. ad-hoc spreadsheets, for the Bill of Materials and the Design for Disassembly criteria;
2. an online survey, for the EoL strategies and ex-ante feedback on the design criteria;
3. focus groups (Krueger et al., 2014) have been organized during a technical meeting, for ex-post feedback on the design criteria.

To double-check the primary data, reports, building plans, pictures of buildings' components/elements, and product declarations (if any) have been collected as a secondary data source and triangulated with expert feedback (Yin, 2018).

Table 8.7: Case studies description.

Country	**Floor area** $[m^2]$	**OE** $[GJ/m^2]$	**Type of building**
1. Parkstad, NL	90	32.4	100 m^2 single-family terraced dwelling.
2. Barcelona, ES	264	37.44	The so-called medianeras, bind opaque walls.
3. Dublin, IR	66	72.36	Private residence.
4. Argelato, IT	407	32.4	Historical rural abandoned manor.
5. Tallin, EE	1766	32.04	Apartments blocks.
6. Ki, SI	240	55.8	Single Family house.
7A. Attica, GR	108	63	Residential apartment.
7B. Attica, GR	109	63	Detached house.

Case Studies

Eight demonstrators were selected in order to analyse different types of relevant buildings in different climate zones in the EU, and various functionalities and renovation interventions, from a historical abandoned manor in Italy to a single-family house in Slovenia and apartments in Estonia. The demonstrators were selected as part of an EU-funded project[2] focusing on the potential of improving the level of circularity of upscalable deep-retrofit solutions. Table 8.7 shows the basic details and a brief description, while Figure 8.11 shows a representative picture, for each demonstrator. A preliminary analysis reveals that the demonstrators' Operational Energy per square meter and per year ranges between 0.64 $GJ/m^2/y$ and 1.45 $GJ/m^2/y$. In particular, the OEs - computed for an average lifespan of 50 years per building - are summarized in Table 8.7.

Data collection: Bill of Materials

First, the so-called Bill of Materials (BoM) related to the in-use materials was obtained for each demonstrator with ad-hoc reclamation audits, i.e. on-site inspections, led by experts. For each identified material, the following information has been collected:

1. building layer (site, structure, skin, services, space plan, stuff);
2. a brief description;
3. the EoL strategy (repaired, reused, refurbished, remanufactured, recycled, not modified, not recoverable);
4. the exact amount (kg);
5. the EE and EC (total and per unit);

The minimum amount of components to be evaluated has been set according to the Pareto rule 80/20, i.e. at least 80% of all the materials within each building. The Pareto rule requirement was set to help practitioners, during the reclamation audit, to avoid wasting time in identifying negligible components in terms of mass and environmental impact. Thus, the reclamation audits focused on the main *Structure*, *Skin* and *Space Plan* layers as demonstrated by Castro et al. (2019). For the EE and EC, the ICE (Inventory of Carbon and Energy, v2.0) database for the built environment, developed by G. Hammond et al. (2011), was adopted in order to balance between too specific and time-consuming LCA process data and the lack of precise information on the in-use

[2] Drive0 website: `https://www.drive0.eu`


(a) Dutch demonstrator


(b) Spanish demonstrator


(c) Irish demonstrator


(d) Italian demonstrator


(e) Estonian demonstrator


(f) Slovenian demonstrator


(g) Greek A demonstrator


(h) Greek B demonstrator

Figure 8.11: Pictures of the eight demonstrators.

materials of old existing buildings. The dataset provides the values of the EE $[MJ/Kg]$ and the EC $[kgCO_2/kg]$ for the most common construction materials (G. P. Hammond et al., 2008).

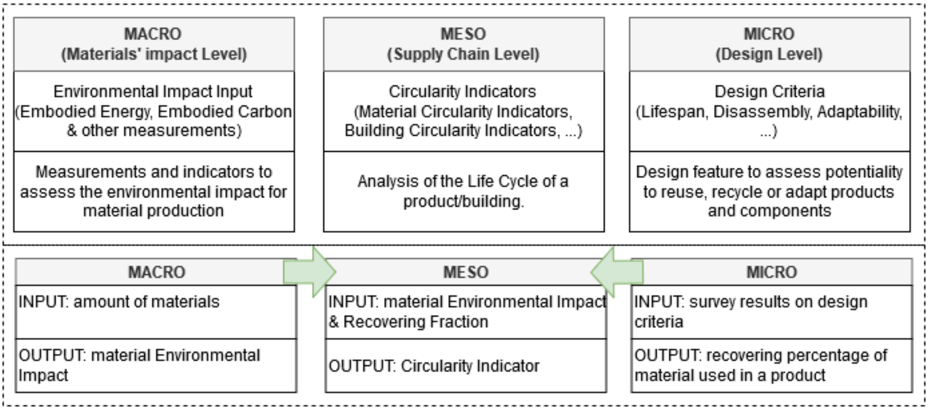


Figure 8.12: Representation of the proposed methodology. It links Macro, Meso and Micro levels for circularity assessment.

Data analysis: linking DfD criteria and Embodied Aspects

Second, a joint evaluation approach, among the Macro, Meso and Micro levels, has been adopted. Figure 8.12 schematically shows the general framework of the adopted approach. The Macro level (material impact) and the Micro level (design) act as input for the Meso level (supply chain). The material level provides the environmental impact of the in-use materials, while the design level provides information on the fraction that can be theoretically recovered within a product. This information feeds the supply chain level in order to compute a CI. At the material impact level, data related to weight, EE, and EC of the materials have been used. At the design level, the DfD criteria proposed by Alba Concept, a simplified version of Durmisevic's criteria (Durmisevic et al., 2006), have been adopted. Table A.7, in the Appendix, lists the four criteria and all the details concerning each design weight.

With respect to the Meso level two indicators have been computed: 1) a *Full* and 2) a *Simplified* version. Both indicators have been quantified in two slightly different versions:

1. the Building Circularity Indicator (Verberne, 2016);
2. the Predictive Building Circularity Indicator (PBCI).

Building Circularity Indicator

The amount of Virgin Material for the product j, $V_j = M_j\,(1 - F_{r,j} - F_{u,j})$, in the BCI formulation, is equal to the total mass of the product M_j minus the fraction of the reused $F_{u,j}$ and the recycled $F_{r,j}$ material. The product Utility X_j, $X_j = (L_j/L_{av,j})\,(U_j/U_{av,j})$, is computed by multiplying the lifetime ratio $(L_j/L_{av,j})$, i.e. the product lifetime L_j over the average lifetime of similar products on the market $L_{av,j}$, for the intensity ratio

$({}^{U_j}/_{U_{av,j}})$, the intensity of use per year U_j over the market average $U_{av,j}$. Due to lack of data, all product utilities were set equal to 1. The amount of unrecoverable waste W_j, $W_j = W_{0,j} + W_{F,j}$, is computed by summing the waste from the linear flow $W_{0,j}$, and from the recovering process $W_{F,j}$. By supposing $W_{F,j}$ equal to 0, i.e. a recovering process 100% efficient (EMF, 2015), the Linear Flow Index (LFI) and the Material Circularity Indicator for product j can be quantified as $LFI_j = {}^{(V_j+W_j)}/_{(2M_j)}$ and

$$MCI_j = \max\left(0, 1 - \frac{0.9}{X_j} LFI_j\right) \tag{8.7}$$

Then, the Product Circularity Indicator PCI_j is computed according to:

$$PCI_j = MCI_j \frac{1}{F_d} \sum_{i=1}^{n} F_{i,j} \tag{8.8}$$

where n is the number of design criteria (in this case $n = 4$ according to Appendix A.4), $F_d = \sum_{i=1}^{n} F_{i,max} = n$ and $F_{i,j}$ is the assigned weight for the design criteria i for the product j.

BCI (Full Version). The System Circularity Indicator SCI_s is computed according to:

$$SCI_s = \frac{1}{M_s} \sum_{j=1}^{J_s} M_j PCI_j \tag{8.9}$$

where $M_s = \sum_{j=1}^{J_s} M_j; \forall j \in s$ is the total mass of all components belonging to the layer s, J_s is the total number of components belonging to the layer s and M_j is the mass of the element j. Finally, the BCI, in its full version, is computed as:

$$BCI_{Full} = \frac{1}{LK} \sum_{s=1}^{S} LK_s SCI_s \tag{8.10}$$

where $LK = \sum_{s=1}^{S} LK_s$ is the sum of all the LK_s weights for each layer, as defined in Table 8.8 and $S = 6$ is the total number of layers.

Table 8.8: Weights LK for each layer.

Layer	**Weight**
Site	0.1
Structure	0.2
Skin	0.7
Services	0.8
Space Plan	0.9
Stuff	1.0

BCI (Simplified Version). The simplified version has to be adopted when a detailed BoM for all the components is not available. In particular, it must be used when only one component belongs to one building layer. Indeed, in this case, if equation 8.9 is adopted, the mass weighting process is meaningless, since

$$SCI_s = \frac{1}{M_s}\sum_{j=1}^{J_s} M_j PCI_j \underset{\mathrm{J_s}=1}{=} \frac{1}{M_1} M_1 PCI_1 = PCI_1 \tag{8.11}$$

and the track of the mass, EE or EC is lost.

Thus, the simplified BCI is defined as:

$$BCI_{Simplified} = \frac{1}{N}\sum_{j=1}^{J} LK_j M_j MCI_j \left(\frac{\sum_{i=1}^{n} F_{i,j}}{F_d}\right) \tag{8.12}$$

where $N = \sum_{j=1}^{J} (LK_j M_j)$ is the normalization factor and J is the total of components for the whole building.

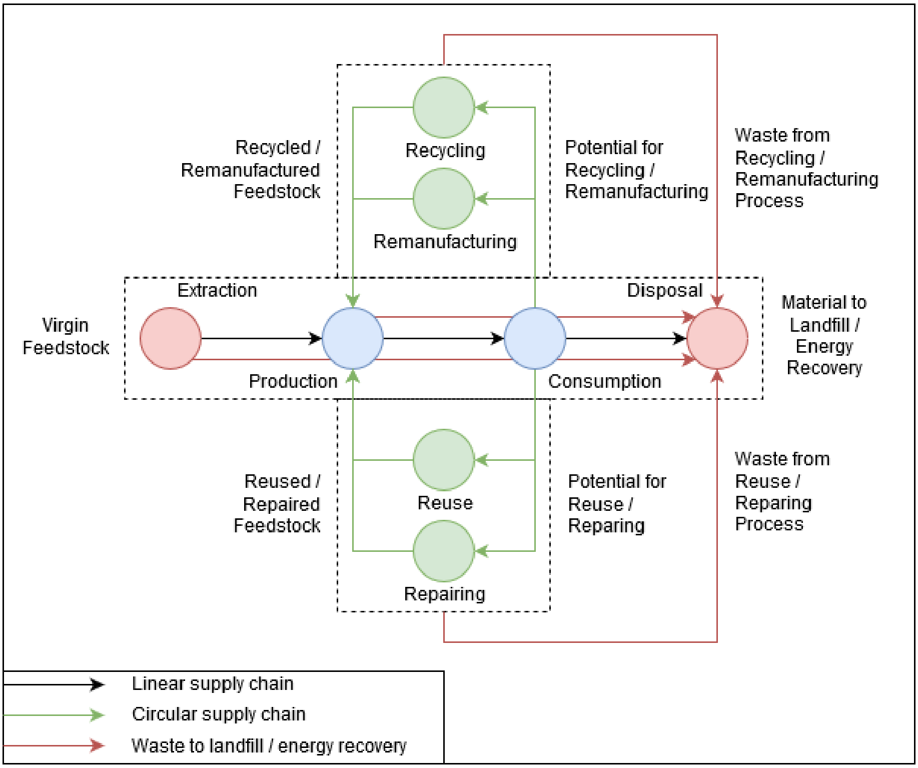


Figure 8.13: Generalization of the Material Circularity Indicator.

Predictive Building Circularity Indicator

The proposed approach could be easily understood by looking at the generalization of the MCI, shown in Figure 8.13. The potential for recycling / remanufacturing / reuse / repairing, and, consequently, the potential unrecoverable waste percentage is predicted by using the design criteria. In other words, the DfD weights are applied directly inside the computation of the MCI and not, as in the BCI, to weight the whole MCI.

PBCI (Full version). Thus, equations 8.7 and 8.8 become:

$$LFI_j = \frac{V_j + W_j}{2M_j} = \frac{V_j + f_j \cdot M_j}{2M_j} \tag{8.13}$$

where $f_j = \frac{\sum_{i=1}^{n} F_{i,j}}{F_d}$. Thus,

$$MCI_j = PCI_j = \max\left(0, 1 - \frac{0.9}{X_j} LFI_j\right) \tag{8.14}$$

The rest of the computation for SCI_s and the BCI is the same.

PBCI (simplified version). The simplified version of the PBCI can be computed according to:

$$PBCI_{Simplified} = \frac{1}{N} \sum_{j=1}^{J} LK_j M_j MCI_j \tag{8.15}$$

where $N = \sum_{j=1}^{J} (LK_j M_j)$ is the normalization factor.

8.2.5 Results and Discussions

Embodied Energy and Carbon

Table 8.9: Mass, Embodied Energy and Carbon per demonstrator.

Country	Total net floor area (m^2)	Mass (t)	Embodied Energy (GJ)	Embodied CO_2 (tCO_2)	Mass (t/m^2)	Embodied Energy (GJ/m^2)	Embodied CO_2 (tCO_2/m^2)	EE/OE [%]
Parkstad, NL	90	120.81	233.34	65.97	1.34	2.59	0.73	7.41
Barcelona, ES	264	92.56	1294.09	85.69	0.35	4.90	0.32	11.58
Dublin, IR	66	91.76	98.54	10.08	1.39	1.49	0.15	2.02
Argelato, IT	407	659.03	3094.54	180.28	1.62	7.60	0.44	19.01
Tallinn, EE	1766	3646.24	8581.84	869.82	2.06	4.86	0.49	13.17
KI, SI	240	433.77	629.49	38.95	1.81	2.62	0.16	4.49
Attica, GR, case A	108	141.22	543.57	39.55	1.31	5.03	0.37	7.40
Attica, GR, case B	109	209.90	678.04	52.69	1.93	6.22	0.48	8.99

Table 8.9 summarizes the results of the first reclamation audits, in terms of mass (t/m^2), Embodied Energy (GJ/m^2) and Carbon (tCO_2/m^2) per square meter, for each demonstrator while all the detailed Bill of Materials are reported in Dario Cottafava, Ritzen, and Oorschot (2020). The values for EE and EC has been calculated thanks to the ICE database (G. Hammond et al., 2011). Each material has been classified into the

six layers of Brand (1995) in Figure 8.14a, 8.14c and 8.14e while Figure 8.14b, 8.14d and 8.14f group the results per EoL strategy. The Embodied Energy per square meter, relating to the Operational Energy for a 50-year building lifespan, counts, in percentage, from a minimum of 2% for the Irish case up to a maximum of 19% for the Italian case, in agreement with previous studies (Azari et al., 2018). The EE percentages relating to the OE are shown in Table 8.9. The total mass for all demonstrators ranges between 1.31 t/m^2 in the Greek case and 2.06 t/m^2 in the Estonian case. The Spanish demonstrator seems to be an outlier with only $0.35t/m^2$; this result can be explained because the assessment covered only the façade, the so-called medianeras. According to previous studies of Manish Kumar Dixit et al. (2010), the EE ranges between $1.49GJ/m^2$ in the Irish case and $7.60GJ/m^2$ in the Italian case, while the EC ranges between $0.15tCO_2/m^2$ in the Irish case and $0.73tCO_2/m^2$ in the Dutch case. The Spanish EE $(4.90GJ/m^2)$ and EC $(0.32tCO_2/m^2)$ is aligned with the other demonstrators results even if the measures obtained reflect only the *Skin*. This last consideration may be explained by the fact that, for almost all demonstrators (except for Irish and the Italian case), the *Skin* of the building, in terms of mass, represents the most impactful layer. Avoiding the Spanish demonstrator where only external walls have been evaluated, in the Estonian, Slovenian and two Greek case studies the *Skin* weights respectively 48%, 59%, 76% and 60% of the total, while for the other case studies the *Skin* weights 29%, 20% and 19%, respectively. In terms of EE and EC, the differences in percentage among the demonstrators are smaller; the *Skin* accounts from a minimum of about 30% for the Irish case to a maximum of 60% for the Greek cases. The second and third most impactful layers are the *Structure* and the *Space Plan*. For the Dutch, the Irish, and the Italian cases, the *Space Plan* is the most impactful layer in terms of mass, while, by looking the EE and EC it is the most impactful only for the Italian demonstrator. This last aspect can be interpreted by the fact that the Italian case study is an ancient traditional manor built for agricultural purposes made in stone-masonry and the composition of internal walls and external ones is almost identical, and in this case no reconstruction/refurbishment has been carried out. The results obtained are in line with previous studies (Castro et al., 2019), although in the present case studies the *Structure* impact has been underestimated due to lack of precise data.

The same considerations can be extended to the EoL strategies for each demonstrator, as shown in Figure 8.14b, 8.14d and 8.14f. Considering this aspect, the declared strategies are more heterogeneous and do not allow any comparison among demonstrators due to different renovation strategies. Although declared strategies appear to be different, one aspect emerges from all demonstrators. All experts declared that they were unable to recover all materials, except for the Estonian and the Slovenian cases, where the cement and the mortar used in the external walls were declared as recoverable. From this first analysis some interesting features emerged. First, an analysis on circularity should not focus only on mass, as shown in Figure 8.14. Results on mass, EE and EC are completely different in percentage over the total. Second, from Figure 8.14 (b, d, f), it emerges that, as declared by practitioners, theoretically almost all materials can be recovered through various EoL strategies. Obviously, this result cannot be completely true in a real renovation process of a building.

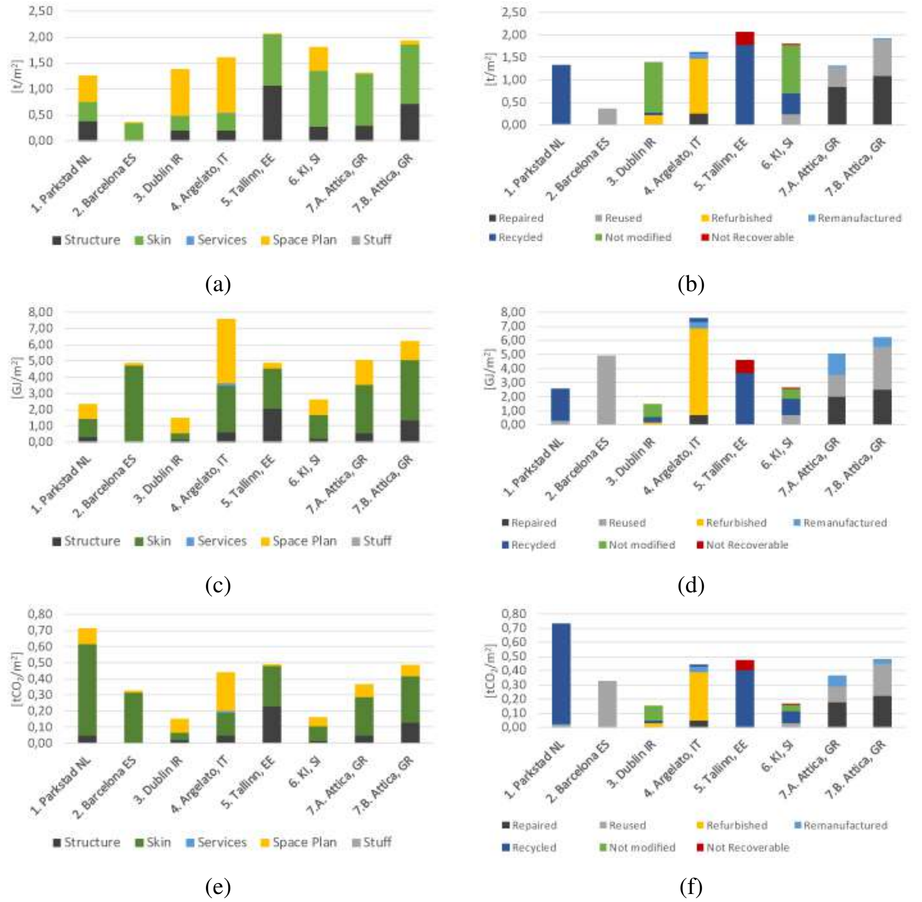


Figure 8.14: Mass, Embodied Energy and Carbon per demonstrator. (a,c,e) Mass $\left(t/m^2\right)$, Embodied Energy $\left(GJ/m^2\right)$ and Carbon $\left(tCO_2/m^2\right)$ per square meter per building layer and (b,d,f) per declared End of Life strategy.

Linking Embodied Energy analyses and DfD criteria

Recoverable percentage

More precise methodologies, instead of the experts' self-evaluations, are required to assess the recovering potential. From Figure 8.14b, 8.14d and 8.14f it is clear that experts, during reclamation audits, overestimate the percentage of recoverable materials. In this subsection, the percentage of the recoverable materials is briefly reported by using DfD criteria as weights for the mass, EE and EC for each component demonstrator. Thus, the recoverable percentage is computed by weighting each material with the DfD criteria in Appendix A.4. Figure 8.15 shows the recovering potential for each demonstrator in terms of mass, EE, and EC. In terms of mass, the percentages vary from a minimum of 24% for the Slovenian demonstrator to a maximum of 86% for the

Estonian case. The other demonstrators' percentages lie between 30% and 60%. The Spanish recoverable percentage is much lower (18%) than the other demonstrators since the DfD assessment refers only to the external walls (a component which is intrinsically harder to disassemble). As discussed by Arora et al. (2019) for the residential built environment in Singapore, the material outflow, from renovation or demolition, can be used to supply the secondary market, and partially satisfy the inflow demand of components and elements for new buildings. They evaluated the material outflow of concrete, steel (skin, and structure layers), windows, doors and accessories (space plan, services, and stuff layers) which count for about the 16%, 20%, 13%, 13%, and 12% respectively. The percentage for recoverable materials, described above for the eight European demonstrators, thus, can be interpreted as a maximum percentage of potentially available outflow of materials and components from a demolished building, and it can partially satisfy the inflow demand in a circular perspective. For the Estonian case, which has a higher recoverable percentage, the result can be explained because the building already had thermal insulation, a component that is easily detachable. Moreover, percentages seem to not change too much among mass, EE and EC for the same demonstrator. Generally, results change by 2%, except for the Irish case (6%) and the Slovenian one (4%). Thus, for these case studies, by assuming an uncertainty lower than 6%, choosing EE or EC as unit of measure to compute the recoverable percentage is irrelevant, as previously noted by G. P. Hammond et al. (2008). The same finding could be easily proved and extended to buildings with a similar composition and age.

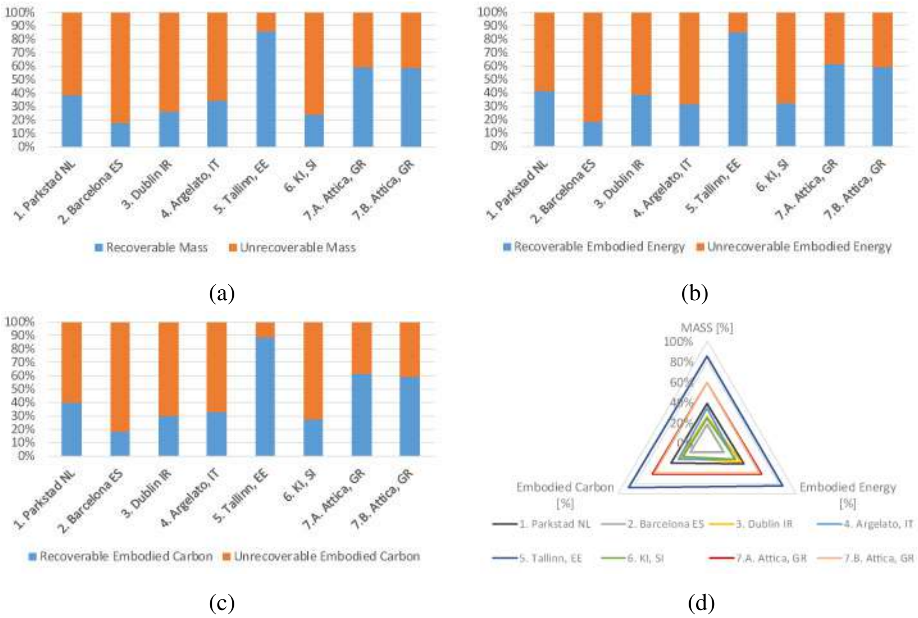


Figure 8.15: Recoverable percentages per demonstrator. Mass (t/m^2), EE (GJ/m^2) and EC (tCO_2/m^2) recoverable percentage.

BCI and PBCI (Full version)

Finally, two different CIs have been computed with two different methodologies. The first, named BCI_{Full}, follows closely the procedure proposed by Verberne (2016) with the simplified design criteria listed in Table A.7, while the second, named $PBCI_{Full}$, refers to Equation 8.13. The difference between the two methods is where the DfD weights are applied. In the first one the DfD weights are used to compute the PCI by weighting the MCI for each component, while the proposed approach applies the DfD weights directly to compute the MCI, i.e. to quantify the recovering potential. This choice can help practitioners during a reclamation audit, or during the design phase, to better recognize the real recovering potential of each component. Results are shown in Table 8.10 and in Figure 8.16 in terms of mass, EE and EC.

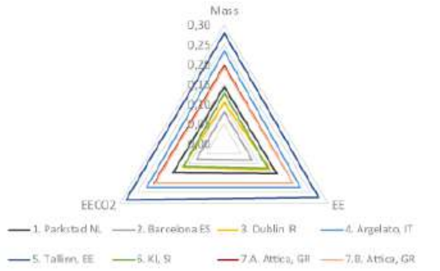
The best performing building is the Estonian demonstrator, with BCI equal to 0.28, 0.27 and 0.28 with respect to the mass, EE and EC respectively, while the worst, avoiding the Spanish one, is the Irish demonstrator with BCI equal to 0.10, 0.13 and 0.12. The values obtained for the BCI partly reflect the previously-discussed results in terms of recovering potential and are highly dependent on the interpretation of the experts' judgment during the reclamation audit. Finally, from Table 8.10 and Figure 8.16 it emerges that the proposed approach for the PBCI shows slightly higher values than the BCI. The distance between the two indicators, i.e. the difference between the values, in terms of mass, EE and EC, is quite constant and never higher than 0.05. This small difference, apparently negligible, should not be neglected. Indeed, within this section the initial hypothesis about the product Utility, i.e. $X_j = 1, \forall j = 1,2,\ldots J$ was done for all the components. Thus, the differences between the two indicators are almost constant.

Table 8.10: Full and Simplified versions of the circularity indicators. Building Circularity Indicator (BCI) and Predictive Building Circularity Indicator (PBCI).

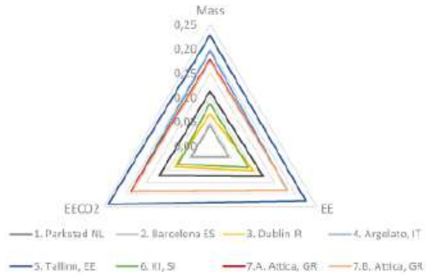
	Simplified Version						**Full Version**					
Demonstrators	**F_i inside MCI (PBCI)**			**F_i outside MCI (BCI)**			**F_i inside MCI (PBCI)**			**F_i outside MCI (BCI)**		
	Mass	**EE**	**EC**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**
1. Parkstad NL	0.29	0.31	0.29	0.23	0.25	0.23	0.14	0.15	0.15	0.11	0.13	0.12
2. Barcelona ES	0.18	0.18	0.18	0.10	0.10	0.10	0.08	0.08	0.08	0.04	0.04	0.04
3. Dublin IR	0.22	0.29	0.25	0.15	0.23	0.18	0.10	0.13	0.12	0.07	0.10	0.08
4. Argelato, IT	0.26	0.25	0.25	0.20	0.18	0.19	0.23	0.22	0.22	0.20	0.18	0.18
5. Tallinn, EE	0.62	0.58	0.63	0.61	0.52	0.58	0.28	0.27	0.28	0.23	0.22	0.24
6. KI, SI	0.23	0.26	0.23	0.15	0.19	0.15	0.13	0.13	0.12	0.09	0.09	0.07
7.A. Attica, GR	0.37	0.38	0.38	0.33	0.35	0.35	0.20	0.20	0.20	0.18	0.18	0.19
7.B. Attica, GR	0.37	0.38	0.37	0.33	0.34	0.33	0.19	0.20	0.20	0.17	0.18	0.18

BCI and PBCI (Simplified version)

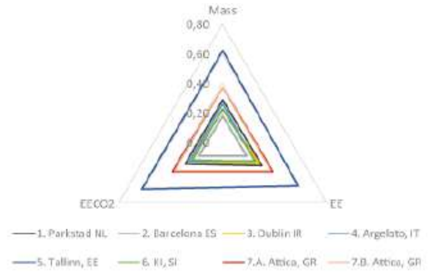
Results from $BCI_{Simplified}$ and $PBCI_{Simplified}$ (Equation 8.12 and 8.15) are summarized in Table 8.10, in Figure 8.16c and 8.16d. All the values of the simplified version are higher than the full version of the indicator. Variations are higher for the PBCI than the BCI. With respect to the PBCI, the minimum difference corresponds to the Italian demonstrator (0.03) while the maximum difference is related to the Estonian case study (0.35). Relative to the BCI, instead, minimum and maximum differences correspond to the same two demonstrators but with a wider range, i.e. 0.00 as the minimum and



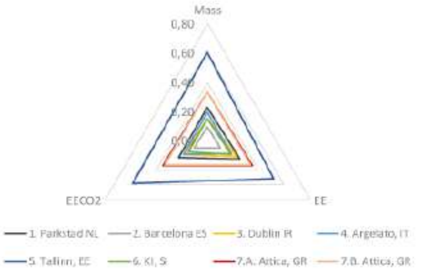
(a) $PBCI_{Full}$



(b) BCI_{Full}



(c) $PBCI_{Simplified}$



(d) $BCI_{Simplified}$

Figure 8.16: BCI and PBCI in Full and Simplified version.

0.38 as the maximum. This significant variation in the results can be explained by the intrinsic differences in the BoM of the buildings. Indeed, the Italian demonstrator BoM is much more detailed - 35 counted components - than the Estonian case - 10 counted components. Indeed, the absolute differences between the simplified and the full indicator depend slightly on the number of components considered per building as shown in Figure 8.17. By excluding some outliers, i.e. the Spanish demonstrator (only *Skin* considered), the Irish case (only two DfD criteria out of four analysed) and the Estonian building (thermal insulation recoverability overestimated), Figure 8.17 and Table 8.11 show how the two approaches tend to converge as the number of components increases. Thus, the more detailed the Bill of Materials is, the closer the results from the two methodologies are (Eq. 8.15 VS Eq. 8.13 and Eq. 8.12 VS Eq. 8.10). This aspect appropriately represents the reason why a simplified indicator should be introduced.

Concluding, the absolute differences between the BCI and the PBCI, i.e. by applying the DfD criteria inside or outside the MCI, are relatively small. They range between a minimum of 0.02 for the Estonian case in terms of mass up to a maximum of 0.08 for the Irish case with respect to mass, EE and EC indistinctly. Thus, by considering a 10% uncertainty, using mass, EE or EC for the building assessment does not change the results. The same consideration is no longer true for single components.

Table 8.11: *Simplified* and *Full* version of the *BCI* and *PBCI*.

Demonstrators		$\Delta BCI_{Simplified-Full}$			$\Delta PBCI_{Simplified-Full}$		
Name	**Total types of components**	**Mass**	**EE**	**EC**	**Mass**	**EE**	**EC**
1. Parkstad NL	23	0.14	0.16	0.14	0.11	0.13	0.11
2. Barcelona ES	7	0.10	0.10	0.10	0.05	0.06	0.06
3. Dublin IR	32	0.12	0.15	0.13	0.08	0.13	0.10
4. Argelato, IT	35	0.03	0.03	0.03	0.00	0.00	0.00
5. Tallinn, EE	10	0.35	0.31	0.34	0.38	0.29	0.35
6. KI, SI	18	0.10	0.13	0.12	0.06	0.10	0.08
7.A. Attica, GR	9	0.18	0.19	0.18	0.16	0.17	0.16
7.B. Attica, GR	10	0.18	0.18	0.17	0.16	0.15	0.15

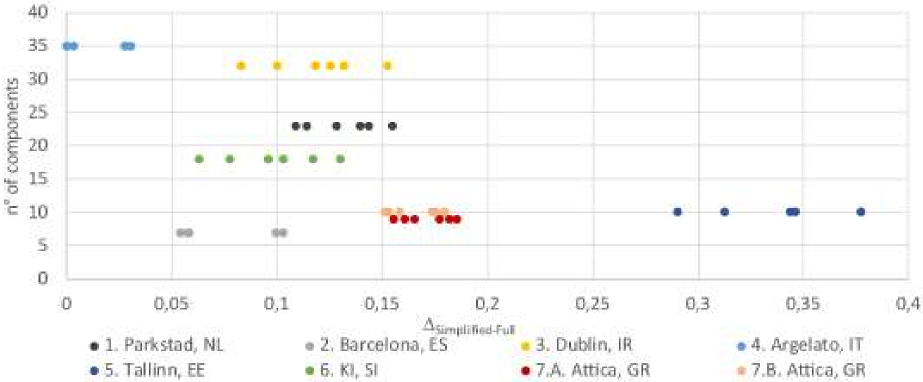


Figure 8.17: Simplified and full indicators vs no. of components within the BoM.

Limitations and further improvements

Some limitations related to the circularity assessment emerged. In terms of regenerative design, the proposed approach - and in general DfD criteria - cannot assess the regenerative potential of a buildings. Indeed, DfD criteria represent a strong tool to assess the recovering potential of materials, components or products but they cannot provide any insight on positive impact on the environment, as they can be simply used to estimate the percentage of a component that can be recovered. To include the regenerative concept, other indicators should be adopted as, among others, the Design for Adaptability and for Flexibility (see section 7.3) which can provide a more holistic assessment. In terms of technical assumptions, instead several other limitations have to be discussed. First, the data collection process for the BoM and the EoL strategies need detailed guidelines for the practitioners and are open to different interpretations. Precise minimum requirements have to be provided to the experts responsible for the reclamation audit to allow meaningful comparisons among different buildings. Indeed, during the reclamation audits of the eight demonstrators, different practitioners identified different priorities. For instance, it is necessary to survey, at least, the *Structure*, the *Skin* and the *Space Plan*. Common in-depth boundary conditions must be defined. In other words, during a reclamation audit one can decide to evaluate a product as a unique component, or to separate each subcomponent. Unclear boundary conditions affect the comparison among different buildings due to different level of details. Since building elements are made of various components in a hierarchy of elements, it is necessary to avoid uncertainty by specifying if the assessment relates to the product itself, its context or to subcomponents (or both). Second, with respect to the DfD criteria further recommendations are needed. A balance between very detailed design criteria and general ones is essential. Too specific and precise criteria mean a very time-consuming process for the reclamation audit and can create difficulties for experts without design knowledge. Too broad and general criteria can result in meaningless results with too high uncertainties. In any case, real examples for the practitioners which conduct the reclamation audit must be provided to avoid misunderstandings during the design evaluation. Third, in this work product utility has been assumed equal to one due to lack of precise data on single component utility. The MCI dependence on the product utility is described in detail in EMF (2015). The MCI is proportional to the inverse of the product utility X, i.e. $MCI \propto 1/X$, when $X > 1$. Thus, the MCI tends to 1 as the product utility X increases, while when $0 < X < 1 \Rightarrow MCI \rightarrow 0$, due to the max function in Eq. 8.7. Due to the simplified hypothesis used in this work, further investigations are needed to understand the impact of each component and/or building layer on the MCI, and consequently, on the PCI, SCI, and $BCI/PBCI$. Fourth, this work focuses on the assessment of existing buildings and is based on the assumption that all materials and components have not been recycled or reused. In a future circular economy, materials and components will be part of infinite cycles, harvested by urban mining, and therefore the chance of being used in a previous stage becomes more realistic. This history of materials and collateral effects on impacts should be well documented, e.g. in the form of a material passport or in a blockchain environment, to predict deterioration and to support future environmental and circularity assessment. Fifth, the data on EE and EC is derived from a single source without differentiation between countries, age (e.g. heritage/historical buildings), construction method, location and climate factors. At a later assessment stage, national or regional data can be applied, validated with on-site measurements and data from material and component suppliers, and handled in a database or platform to improve accuracy. Finally, a lifespan of 50 years has been assumed. This assumption is in line, on average, with the European residential built environment context. The overall methodology is not affected by a change in the buildings lifespan, although percentage results of EE/OE in Table 8.9 will change accordingly. A detailed analysis by changing single building components after renovation interventions is out of the scope of this benchmark study but renovation impacts should be analysed in terms of BCI/PBCI to assess an eventual circularity improvement.

8.2.6 Conclusion

The increase of interest in Circular Economy shifts the attention from Embodied Energy analyses to the use of Circularity Indicators for environmental assessment. Despite the level of attention the Circular Economy is experiencing nowadays, a rigorous connection among Embodied Energy, a common approach for environmental assessment of the built environment, Circularity Indicators and design criteria is still missing.

In this work, two main research questions were addressed, i.e. 1) *"How to improve the environmental assessment of the raw materials used in a Building Circularity Indicator?"*, and 2) *"How to quantify the End of Life potential of materials and building components for recovery by adopting Design for Disassembly criteria?"*. For this purpose, two Circularity Indicators for the Built Environment, the Building Circularity Indicator (BCI) proposed by Verberne (2016) and a new improvement named Predictive Building Circularity Indicator (PBCI), were tested in two different versions, i.e. a *Full* and a *Simplified* version, on eight different case studies in different climate zones in Europe with respect to the components mass, Embodied Energy and Carbon. The Design for Disassembly criteria used in this works - i.e. Types of connection, Connection Accessibility, Crossings, and Form Containment - revealed to be a more realistic indicator to better predict the recovery potential of building components than more common approaches based on the assessments of experts.

In particular, the analysis revealed how, at a building level, varying between mass, Embodied Energy and Carbon induces an uncertainty lower than 10% for both indicators, i.e. BCI and PBCI, with the simplifying initial hypothesis of product utility $X = 1$ for all components (assumption made due to lack of data). The same result cannot be considered true by varying the product utility or by comparing single components. Moreover, the comparison between the Full and the Simplified version of both indicators shows how the differences $BCI_{Simplified} - BCI_{Full}$ or $PBCI_{Simplified} - PBCI_{Full}$ depend on the number of components considered during the Reclamation Audits of the buildings. As the number of components increases, the two approaches converge to a common indicator, while when only few components are considered the simplified version is suggested.

In conclusion, the proposed approach is the first step towards a thorough understanding of how Design for Disassembly criteria impact on circularity but further investigations are needed, such as, for instance, on the ability of DfD principles to correctly predict the recoverability of materials. Indeed, assessing Design for Disassembly criteria results to be a more suitable and accurate approach to evaluate building circularity, although precise comparisons among different buildings still need detailed guidelines for practitioners in order to reduce the subjectivity during the assessment, such as defining strict boundary conditions, declaring the level of detail (e.g. components or subcomponents), and a minimum and common number of evaluated components.

8.3 Input-Output model

In this section a recent application related to the input-output tables will be described. The text of this section is largely based on “COVID-19 impact on the Italian economy: past, present and future scenarios" (Dario Cottafava, Gastaldo, et al., 2021), an assessment of the impacts of the Covid-19 restrictions during 2020 in Italy both in economic and environmental terms.

8.3.1 Introduction

The coronavirus disease 19 (COVID-19) pandemic shocked the entire world. The year 2020 has been characterized by unprecedented national and local restrictions on economic activities and on the freedom and mobility of the citizens (Bonaccorsi et al., 2020). Stay-at-home restrictions, curfews, and total or partial lockdowns deeply affected the lifestyle of citizens, provoked mental health and sleep disturbances (Gualano et al., 2020), and increased poverty, exacerbating income inequalities (Buheji et al., 2020). None has been left untouched. Firms and industries (Atkeson, 2020) as well as financial markets (Ashraf, 2020) have been strongly impacted by the regulations and laws urgently adopted to reduce the diffusion of the virus.

By contrast, the sudden interruption of the industrial production and of a large part of human activities allowed to evaluate their impact on the environment (Rutz et al., 2020). For instance, He et al. (2020) compared the Air Quality Index (AQI) of different Chinese cities before and during the lockdowns. In the cities affected by lockdown restrictions, the AQI, measured as particulate matter concentration (PM2.5), dropped by 14.07 μgm^{-3}, while in neighbouring, unaffected cities the PM2.5 dropped by 7.05 μgm^{-3}. In the first half of 2020, globally, CO_2 emissions decreased abruptly by 8.8% with respect the same period in 2019; such a reduction in greenhouse gases (GHG) emissions is larger than that calculated for the World War II period (Z. Liu et al., 2020).

In the past months, the effort of academics, practitioners, and decision- or policy-makers to analyze, evaluate, and predict the short and long-term impact of the COVID-19 and related policies has been astonishing. The economic losses (Nicola et al., 2020), workforce reduction (Santos, 2020), social and psychological impact (Cerami et al., 2020), mortality, death rate, spread of the virus (Atkeson, 2020), and air emission reduction (He et al., 2020) due to the COVID-19 pandemic, among others, have been evaluated by dozens of different methods, such as online anonymous surveys (Cerami et al., 2020), input-output (IO) model (Haddad et al., 2020), susceptible - infected - recovered (SIR) model (Toda, 2020), and carbon footprint analysis (Rugani et al., 2020), at the national and global scale.

However, a systematic account of the interplay between economic and environmental impacts of the current pandemic seems to be still missing. To fill this gap, we propose that in the current global crisis, a particularly powerful approach to assess the economic impact of the coronavirus may take advantage of the analysis of input-output tables and of the input-output inoperability model (IIM). Despite in the past IIM has been applied to a wide range of scenarios (see section 7.2), its use as a policy evaluation tool for the COVID-19 pandemic has been limited (Haddad et al., 2020).

Moreover, a precise assessment of the economic effect of the first lockdown in the period of February-August in different countries is still missing. Moreover, because of the rapid and sudden variations in the R_0 index (Germann et al., 2006; Viceconte et al., 2020), it is nowadays necessary, more than ever, to predict the impact of restrictive measures on the economic sectors of a country quickly and accurately. Indeed, because of the nearly daily introduction of new regulations to fight the spread of the COVID-19, modelling and predicting the behaviour of highly uncertain national economies is still an open challenge.

On top of these considerations, in this section, the effect of the lockdown restrictions on the Italian national economy during the period March-August has been evaluated through the use of the input-output tables and the inoperability methodology. By reconstructing all the Italian national decrees between March and June 2020, the day-by-day and total economic losses as well as the GHG emission reduction, for the whole Italian economy, and per economic sector, have been evaluated. The adopted methodology consists of three steps: 1) the reconstruction of all restrictions during the period March-June, 2) the simulation of the effect of the past lockdown and identification of the most economically impacted sectors and of those avoiding most emissions, and 3) the simulation of five future scenarios to forecast the effect of the current partial restrictions. The methodology has been used to analyze the Italian economy as a case study, during the period from March to August 2020 by evaluating 1) the trend of the open/closed sectors through the inoperability, 2) the economic loss, and 3) the air emissions reduction per sector due to the closed sectors.

The contribution of this work to the existing literature is twofold. First, it contributes to the ongoing debate on the economic and environmental impact of Covid-19 pandemic, by framing the analysis in an original and innovative empirical setting. Second, it contributes the literature on economic resilience by shedding light on sector-level dynamics that can be leveraged to customize industrial policies to promote recovery.

The rest of this section is structured as follows. In section 8.3.2 the adopted methodology, based on the IOTs, inoperability, and national air emission accounting is described in detail, focusing on the reconstruction of the Italian legislations adopted during the first wave in the March-June 2020 period as a case study. In section 8.3.3 the main findings are presented, highlighting the most impacted economic sectors in Italy and the interrelationships among different sectors. Finally, the impact of the ongoing restrictions is inferred by simulating five scenarios related to partial lockdown, pointing out the limitations and future improvements of this analysis.

8.3.2 Materials and methods

A three-step analysis process is adopted in order to simulate the past, present, and future of the Italian national economy. First, a detailed reconstruction of all national decrees and laws during the period March-June is described. Second, the effect of the past lockdown measures based on the adopted decrees has been evaluated thanks to the use of the IIM, emphasizing the most impacted sectors. Third, based on the current partial lockdown measures, five future scenarios have been simulated to predict the possible effects of the second wave restrictions.

The past, present, and future scenarios of the Italian economy, used as a relevant case study (Stake, 1995), have been analyzed by evaluating:

1. the trend of the open/closed sectors.
2. the economic losses, per sector and total.

3. the air emissions reduction, per sector and total, due to the closed sectors.

By analyzing the day-by-day effect of the open/closed sectors through the inoperability, the inter-dependency among economic sectors was pointed out.

The relevance of the Italian case study is undoubted. Italy was the first European country and second in the world (after China), to be deeply impacted by COVID-19. Moreover, it was the first country to adopt a national lockdown. Because other countries, following the Italian example, adopted immediately a total national lockdown, the analysis of the first months in Italy has a unique relevance. Indeed, in Italy, the restrictions during the "first wave" were adopted gradually. This aspect allows to analyze the effects of punctual restrictions on the economy, i.e only on targeted sectors. Thus, Italy, as an information-rich case study, allows an analytical generalization of the findings to similar economies (R. Johansson, 2007).

Case study

The Italian Government declared a state of emergency on January 31st 2020 (Italian Government, 2020), exactly one month after China's warning of a cluster of pneumonia of unknown etiology (then identified as new coronavirus Sars-CoV-2) and the day after the World Health Organisation declared the Coronavirus as a public health emergency of international concern (WHO, 2020).

In Italy, the emergency was mainly regulated through the adoption of Decree-Laws (*Decreti Legge*, D.L.), Prime Ministerial Decrees (*Decreti del Presidente del Consiglio dei Ministri*, DPCM) and Ordinances of the Ministry of Health (*Ordinanze del Ministero della salute*). The latter are ordinances that the Minister of Health has the power to enforce in extraordinary and urgent circumstances that have mainly focused on preventive measures such as hygiene procedures, but also on restrictions to the freedom of movement and assembly. These containment measures were imposed also through Decree-Laws which, however, have primarily affected the freedom of economic initiative. In particular, the Decree-Law no. 6 of February 23rd 2020 is the relevant legal basis of the DPCMs adopted in the following period. On the advice of the Minister of Health, the Prime Minister was entitled to order restrictive measures regarding municipalities where at least one person was infected and the source of transmission was not known. The potential measures included the prohibition of access to and departure from the concerned area, the interruption of public and private events, public offices, school activities, public opening of museums and other places of culture to the public, working activities for certain categories of companies, and the closing of certain commercial activities.

On February 23rd 2020 the Italian Prime Minister adopted the first DPCM (IG, 2020h) to prevent people from moving and interrupt school attendance, cultural activities, as well as working and commercial activities with the exception of those offering essential goods and services, in the municipalities of northern Italy most affected by the pandemic (namely, within the regions Lombardia and Veneto). The DPCMs issued on February 25th (IG, 2020i) and March 1st 2020 (IG, 2020b) introduced new measures concerning the management of sport events and school activities, among other interventions. Moreover, they extended the restrictions to other municipalities.

The transition from localised to national restrictions occurred with the DPCM of March 8th 2020 (IG, 2020l). At the national level, the activity related to cultural events and places, pubs, and clubs was suspended, while catering and commercial businesses were affected by opening hours restrictions and distancing rules. In some regions and municipalities, most of which already regulated by the February DPCM, more stringent measures were implemented. The following day, through the DPCM of March 9th 2020 (IG, 2020m) these measures were extended to the national territory. Strict measures that brought the country in a period of lockdown were implemented until the end of April, when a gradual re-opening was allowed.

All the regulations adopted by the Italian government during the period from March to June 2020 are listed and described in detail below. The restrictions were mainly put into action through the adoption of DPCMs, generally the day after the DPCM notification. Table 8.12 summarizes all the concerned DPCMs, including, first, the restrictions, and, second, the opening measures. Table 8.12 describes the main economic sectors affected by the lockdown measures, as well as their code in the Statistical Classification of Economic Activities in the European Community (NACE). The full list of NACE codes and the relative description for each sector are provided in Appendix A.5.1.

The list focuses on sectors whose activity was interrupted, totally or partially:

- DPCM March 8th 2020: the first measures affected entertainment venues and recreational activities (IG, 2020l).
- DPCM March 9th 2020: the rules were tightened up, including also the fields of sport and physical well-being (IG, 2020m).
- DPCM March 11st 2020: new limitations were added to the suspensions announced in the DPCMs March 8th and 9th, mainly involving retailers (with the exception of those supplying essential goods) and restaurant owners. Limitations had to remain in place until March 25th (IG, 2020e).
- DPCM March 22nd 2020: the previous measures were extended until April 3rd, including also the manufacturing sector. It was the first decree directly encompassing the manufacturing sector (IG, 2020g).
- DM March 25th 2020 (amending DPCM March 22th 2020): non-strategic productive sectors were required to comply with the new rules (IG, 2020j).
- DPCM April 1st 2020: the effectiveness of the provisions of the DPCMs adopted from March 8th to March 25th was extended until April 13rd (IG, 2020a).
- DPCM April 10th 2020: the effectiveness of the provisions of the DPCMs adopted from March 8th to March 25th was extended until May 3rd with minor changes involving the productive and service sector. The DPCM approved also the reopening of stationery shops, bookshops, and retail sale of kids clothing from April 14th (IG, 2020c).
- DPCM April 26th 2020: the beginning of the so-called “phase two”, characterised by a progressive easing of the restrictions. Most notably, the DPCM announced that, from May 4th, the manufacturing sector, together with constructions and wholesale were allowed to operate (IG, 2020k).
- DPCM May 17th 2020: the other activities under restriction were sequentially allowed to open, starting from cultural places, retail trade, restaurants, and activities related to personal care from May 18th; sport facilities from May 25th; and finally,

Table 8.12: DPCM Measures

DPCM	Date	NACE	Restrictive Measures (Suspension of activities)
DPCM March 8th 2020	March 9th	R90 - J59.14	Theatres' and cinemas' opening
		R91	Museums' and cultural places' opening
		R92	Gambling and betting activities
		R93.2	Amusement and recreation activities (e.g., dance studios and discotheques)
DPCM March 9th 2020	March 10th	R93.1	Sport facilities' opening (e.g., gyms, sport centres, and swimming pools)
		S94.99	Cultural and recreational centres
		S96.04	Well-being centres activities
DPCM March 11st 2020	March 12th	G47	Retail trading activities with the exception of those supplying food products and other essential goods (e.g., computer equipment, automotive fuel, household equipment, medical goods, and newspapers) and those not sold in stores
		I56	Food and beverage service activities (e.g., cafes, pubs, restaurants, ice-cream parlours, and confectioneries) excluding home deliveries, canteens, catering services and activities located along the highway, in stations, airports, and in hospitals
		S96.02	Personal service activities (e.g., hairdressers, barbershops, and other beauty treatments)
DPCM March 25th 2020	March 26th	B7 - 8	Mining activity different from the extraction of coal, crude petroleum, and natural gas
		C12	Manufacture of tobacco product
		C13 - 14 - 15	Manufacture of textiles, leather and related products (with some exceptions for technical and industrial textiles)
		C16	Manufacture of wood products
		C23	Manufacture of glass and glass products (with the exception of those for medical use), manufacture of cement, lime, and plaster
		C24 - 25	Manufacture of basic metals and fabricated metal products
		C26 - 27	Manufacture of computer, electronic and optical products, and electrical equipment (with the exception of electromedical equipment)
		C28 - 29 - 30	Manufacture of machinery, motor vehicles, and other transport equipment
		C31 - 32	Manufacture of furniture and other goods different from medical instruments
		F41 - 43	Construction of buildings, demolition and site preparation, building completion and finishing
		G45 - 46	Wholesale trade, except for basic commodities (e.g., agricultural raw materials and animals, food, beverages and tobacco, pharmaceutical goods, newspapers, agricultural machinery, and fuels)
		L68 - N77	Real estate, rental and leasing activities
		M73	Advertising and market research
		N78	Employment and human resources provision activities
		N79	Travel agencies and tour operators
		N80 - 81 - 82	A limited number of activities in the service sectors (e.g., landscape services, office administrative and support activities) and repair of household goods, except for computers and communication equipment
			Opening Measures
DPCM April 10th 2020	April 14th	A2	Forestry and logging
		C16	Manufacture of wood products, not including furniture
		C26.1 - 26.2	Manufacture of electronic components, computers and peripheral equipment
		N81.3	Landscape service activities
		U99	Activities of extraterritorial organisations and bodies
DPCM April 26th 2020	May 4th	B7 - 8	Mining activity different from the extraction of coal, crude petroleum and natural gas
		from C12 to C32	Manufacturing
		F41 - 43	Construction of buildings and other construction activities
		G45 - 46	Wholesale trade
		L68 - N77	Real estate, rental, and leasing activities
		M73	Advertising and market research
		N78	Employment and human resources provision activities
		N80 - 81 - 82	A limited number of activities in the service sectors (as landscape services, office administrative and support activities) and repair of household goods, except for computers and communication equipment
		G47.76	Retail sale of flowers, plants, seeds and fertilisers
DPCM May 17th 2020	May 18th	G47	Retail trading activities
		I56	Food and beverage service activities
		R91	Museums and cultural places
		S96.02	Personal service activities
	May 25th	R93.1	Sport facilities opening (e.g., gyms, sport centres, and swimming pools)
	June 15th	R90 - J59.14	Theatres and cinemas
DPCM June 11st 2020	June 15th	R92	Gambling and betting activities
		S94.99	Cultural and recreational centres
		S96.04	Well-being centres activities

theatres, concert halls, and cinemas from June 15th (IG, 2020f).

- DPCM June 11st 2020: from June 15th new rules for the re-opening applied also to gambling and betting activities, cultural and recreational centres, well-being centres. Recreational activities taking place in dance studios and discotheques remained closed (IG, 2020d).

Methodology

To predict the impact of the sequential suspensions that affected different economic sectors at different times, the IIM (Haimes et al., 2005a; Haimes et al., 2005b), based on the input-output (IO) model (W. Leontief, 1986; W. W. Leontief, 1951a; W. W. Leontief, 1951b), has been used (see section 7.2 for further details).

The inoperability of the different economic sectors has been modeled according to Eq. 7.26. The values of $\mathbf{x}$, $\mathbf{A}$, and $\mathbf{c}$ were obtained from the Eurostat database (EUROSTAT, 2020d), and are, thus, expressed in million euros. To translate the DPCM restrictions into correct q_i values representing the real limitations to economic sectors, a value of 0 has been assigned to sector sub-classes allowed to operate (i.e. fully open sector) and 1 to those enforced to suspend their activity (i.e. fully closed). The Ministerial Decrees identify activities to be suspended through their ATECO code, which is the classification of economic activities employed by the Italian National Institute of Statistics (ISTAT, 2009) and represents the national version of NACE codes. The IOT employed in this study was sourced by Eurostat (EUROSTAT, 2020d), which provides it at the aggregate level of the NACE categorization. Thus, first, a dichotomous 0-1 value was assigned to each sub-class, and multiplied with its production (for NACE codes from B to Q) or its gross value added (for NACE codes from R to U). Then, the sum of the resulting values was divided by the global sector's production (or gross value added). The result was a value between 0 and 1 for every relevant NACE code, i.e., the weighted average of the of the inoperabilities of its corresponding ATECO subclasses, revealing the degree of inactivity of the sector. The related codes are listed and defined in Appendix A.5.1, Table A.8. The inoperabilities of the Italian activities according to the DPCM are reported in Appendix A.6, Table A.9. The obtained q_i values were fixed as the minimum for the period of validity of the DPCM, to account for the possible loss of production of the open subsectors as a consequence of the interdependence from suspended ones. The time $t_0 = 0$ refers to the DPCM of the 8 March 2020, as the previous DPCM referred to geographically limited zones in Italy. The simulation was ran for 200 days ($t_{fin} = 200$), i.e., approximately 6 months.

Reduced air emissions

Through the environmental extended input-output tables (De Haan et al., 1996), it is possible to evaluate the total air emissions per sector. Eurostat, through the env_ac_ainah_r2 database, provides extended tables for several air emissions (EUROSTAT, 2020b): carbon dioxide without emissions from biomass (CO_2) and from biomass used as fuel (biomass CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulphur hexafluoride (SF_6), nitrogen oxides (NO_X), sulphur oxides (SO_X), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$). According to the Eurostat Manual

Tukker et al. (2006), the total direct and indirect emissions of pollutants per sector can be computed according to eq. 7.18.

In this work, the avoided greenhouse gases emissions (see eq. 7.29) have been calculated in thousands of tonnes of $CO_2 eq.$. According to (EUROSTAT, 2020b) the GHG total emissions environmental pressure is computed through the global warming potential as

$$GHG = CO_2 + N_2O + CH_4 + HFC + PFC + NF_3 + SF_6 \tag{8.16}$$

where the emissions of N_2O, CH_4, HFC, PFC, NF_3, SF_6 are expressed in $CO_2 eq.$ through conversion factors (298 for N_2O, 25 for CH_4, etc.).

Industry resilience factors

As noted from Eq. 7.27, the values k_{ij} of the industry resilience matrix **K** define the rapidity of reaction of a sector to suspensions/re-openings. Thus, they define both the response rate to the closing of different interconnected sectors and the recovery rate after the restrictions are removed. The matrix **K** is determined by the capital investments, both by the public and private sectors. Because it was not possible to determine precisely neither the effect of public funding to businesses and private citizens during the months after the lockdown nor the reactivity of open sectors to closed ones, in this work, three values of K have been considered to conduct a sensitivity analysis on the final results. The industry resilience matrix $K = \text{diag}(k_i)$ was first constructed with $k_i = 0.2$, and then the simulations were ran with $k_{i,min} = 0.1$ and $k_{i,max} = 0.3$. These values give rise to three distinct cases: 1) $k_{i,min}$ represents a full recovery of all sectors in 1–3 months, i.e., a slow recovery process, 2) $k_{i,max}$ represents a fast recovery (less than two weeks), and 3) k_i, the average value, represents an intermediate case where all economic sectors recover in one month.

Table 8.13: Different scenarios for increasing restrictions measures.

Scenarios	**Restriction description**	**Affected sectors**
Scenario 1	1) sports activities	R93
Scenario 2	1) sports activities, 2) entertainment industry	R93, R90-92
Scenario 3	1) sports activities, 2) entertainment industry, 3) food and accommodation	I, R93, R90-92, S96
Scenario 4	1) sports activities, 2) entertainment industry, 3) food and accommodation, 4) reduced mobility	I, L68B, R93, R90-92, N77, N78, N79, S96
Scenario 5	1) sports activities, 2) entertainment industry, 3) food and accommodation, 4) reduced mobility, 5) retail shops	G45, G46, G47, I, L68B, J59_60, R93, R90-92, N77, N78, N79, S96

Scenario analysis

Using the results for the first wave lockdown in Italy, to understand and predict the effects on the national economy of the ongoing second wave measures, five partial lockdown scenarios have been analyzed. Because all countries, all over the world, experienced the deep impact of a total lockdown, national governments are trying to limit a second total lockdown while preserving public health safety. Thus, different countries, such as Spain, France, and Italy, are imposing partial restrictions depending on the value of the R_0 index, available beds in public and private hospitals, and other criteria. The second wave restrictions regard, firstly, collective and thus dangerous activities such as sports and entertainment, food and beverage, as well as accommodation services, and secondly the retail, trade, and mobility (i.e. travel agency and tour operators) sectors. According to this rationale, Table 8.13 summarizes five scenarios, with increasing restrictions. In the simulated scenarios, an inoperability value was assigned to the sectors listed in table 8.13 according to their respective maximum value as computed for the first wave and summarized in section A.6 in the Appendix. Scenario 1 and 2 represent the first reaction of governments to the spread of the COVID-19. These first restrictions affect mainly collective activities (e.g., sports, entertainment, and cultural industries). Scenario 3, instead, refers to the largely adopted measures against the Covid-19 when the diffusion of the virus starts to increase exponentially and involves the closing of bars, restaurants, and night-life activities, as well as caterings and public events. Finally, scenario 4 and 5 simulate those occurring when the national healthcare system of a country approaches the limit of available hospital beds. These are the last trench before a total lockdown, and they affect retail shops, shopping centers, and mobility (e.g. interregional and intercity mobility of the citizens).

8.3.3 Results and discussion

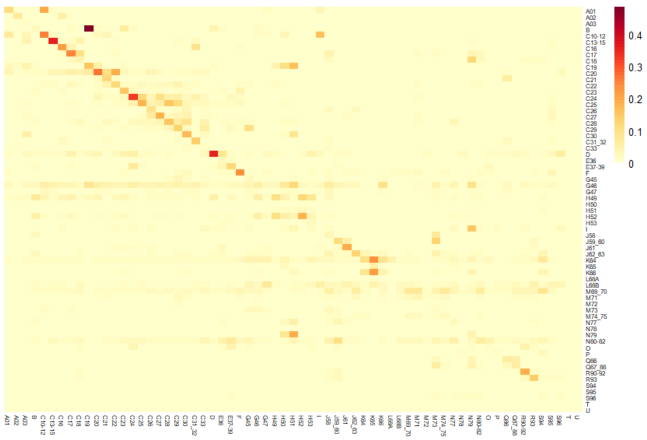
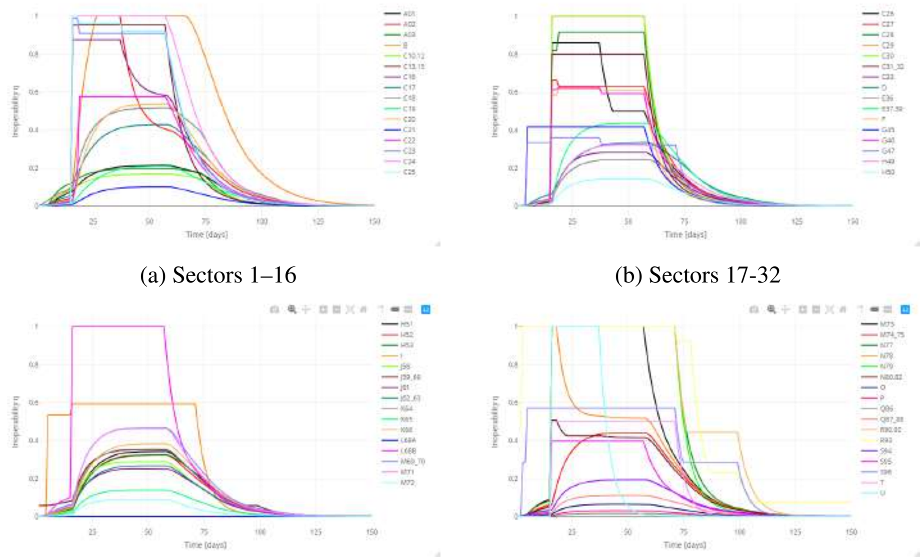


Figure 8.18: Heatmap representation of the interdependency matrix A

Figure 8.18 shows the heatmap representation of matrix A (Eq. 7.21). The color scale represents the intensity of the exchanges between two sectors. The rows-to-columns intersections depict the exchanges from the sector corresponding to the row to the one corresponding to the column, and viceversa for columns-to-rows intersections. Clearly, each sector strongly depends on self-exchanges (diagonal of the matrix). The most interconnected sectors are those belonging to NACE code-groups M, N, Q, R, and S, i.e. the activities related to general services (such as repair of computers, rental, leasing, and employment, activities). Group C (manufacturing sectors) is mainly tied with itself. The same occurs for group H (essential transport services), although this is also a main contributor of groups A, B, and C.

Case study: italian lockdown impact



(a) Sectors 1–16

(b) Sectors 17-32

(c) Sectors 33–48

(d) Sectors 49-65

Figure 8.19: Inoperability dynamics of economic sectors. During the first 150 days, from the 8th of March to the end of July 2020, for an industry resilience value of $k = 0.2$.

Sector inoperability. This section introduces the dynamics of all economic sectors during the first lockdown in Italy. The effect of the restrictive measures, summarized in section 8.3.2, is described and analyzed in terms of the inoperability of each sector, as previously described in section 8.3.2. Figure 8.19 shows the day-by-day evolution of each sector and the effect of the restrictions for the first 150 days, highlighting the closed and open (i.e. the ones not directly affected by the DPCM) sectors. In particular, the figure shows the *cascade* effect of the closed sectors on the open ones, which after few days decrease their operation. The decay rate is given by the median value of k, $k = 0.2$. The dynamic for the minimum ($k = 0.1$) and maximum ($k = 0.3$) values is reported in section A.7 of the Appendix. The abrupt steps correspond to the days at which a restriction enters into action. Thus, it has been supposed that the affected sector immediately stops its activity from the day after a new measure. On the contrary, for the opening, after the governmental restrictions were raised, it has been supposed that the economic sectors were unable to recover immediately at 100%. The rationale of this hypothesis is to model the post-lockdown hygiene, security and safety measures, as well as the large adoption of smart working practices by many industries and businesses. The day-by-day dynamics shows the impact of the restrictions on all economic sectors, not only the targeted ones. Indeed, all sectors that smoothly increase their inoperability are those that are only affected by the closure of the others.

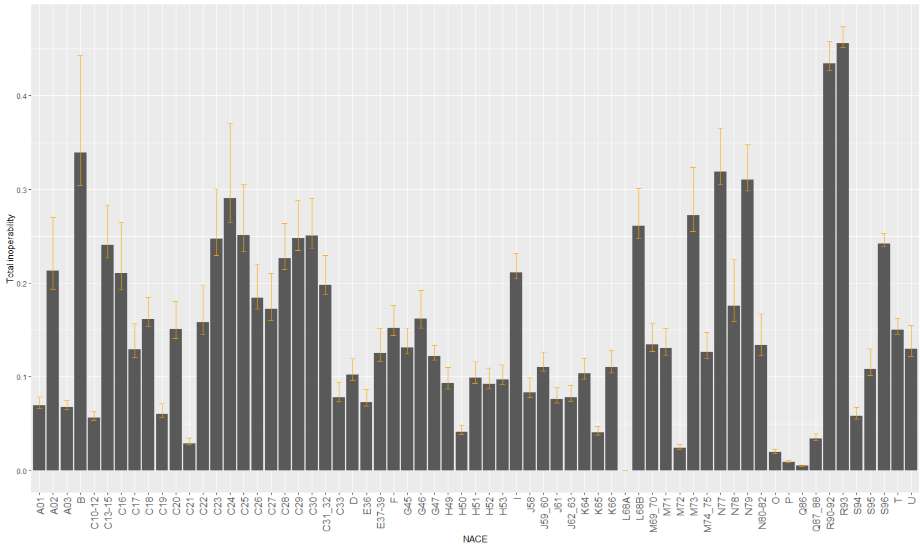


Figure 8.20: Total inoperability (%) over a period of 200 days. The values of the histogram are those for $k = 0.2$, with error bars related to $k_{min} = 0.1$ and $k_{max} = 0.3$.

On top of these dynamic representations of the model, figure 8.20, shows the percentage of the time a sector was closed during the period of 200 days, i.e., the average of q for each sector. The histogram is calculated for a value of $k = 0.2$, and the error bars refer to a industry resilience k of $k_{min} = 0.1$ and $k_{max} = 0.3$. The five most affected sectors, in terms of closing time due to the Italian DPCMs, were R93 (sports activities, amusement, and recreation activities), R90-92 (creative, arts, and entertainment activities), B (mining and quarrying), N77 (rental and leasing activities), N79 (travel agency and tour operators). In particular, R93 and R90-92 were the two sectors closed by the DPCMs for the longest time, starting from the 8th of March, i.e. since the beginning of the restricions. N79 and N77 (travel agency and rental activities), instead, were closed only between the 23rd of March and the 4th of May, but were strongly affected by their interdependence with other sectors. Finally, sector B (mining and quarrying) was not completely closed by the decrees. Only the raw materials extraction was closed from the 23rd of March to the 4th of April, while petrol and gas-related activities had not been touched. Thus, although the DPCMs only partially limited the mining and quarrying sector, this was strongly affected by the lockdown. This is a direct consequence of the interdependence of economic sectors, as can be seen from figure 8.18. Indeed, group B is one of the few economic sectors that depends only on essential services (group H) such as land, water, air transport, warehousing, and postal activities, which were obviously not closed, because all other activities depend on them. The first sector directly affected by B is C19 (manufacture of coke and refined petroleum products), to which many manufacture sectors are strictly tied.

Finally, it is noteworthy to point out the asymmetry of the error bars due to the different values of k, i.e. the industry resilience. The lowest value is for $k = 0.3$, which corresponds to a very fast response of a sector to shocks. Indeed, when $k = 0.3$, nearly all sectors recover full operability in less than one month. The maximum inoperability, instead, is found for $k = 0.1$, when most sectors recover in times of one–two months, though sector B does not fully recover even after 3 months. This result is reflected by the error bar on top of the B column in figure 8.20, which is the largest one. Thus, the interdependence of a sector from the other ones may be inferred from the size of the error bar. For instance, although R90-92 and R93 were closed nearly all the time, they are not very dependent on other sectors and thus recover quite fast. On the contrary, sectors such as C (manufacturing activities), A02 (forestry), or N (rental, employment, and travel activities) experience a slower recover.

On top of these results, the economic losses and the air emissions reduction have been calculated to quantify the effect of the lockdown measures.

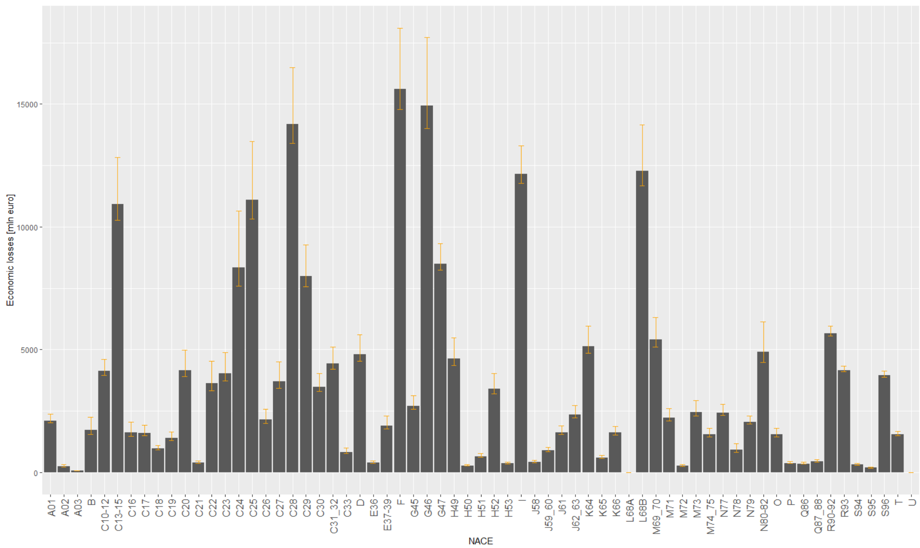


Figure 8.21: Total economic losses per sector during the first 150 days. From the 8th of March (first day of lockdown in Italy).

Economic Losses. Figure 8.21 shows the total economic losses per sector in Italy (in millions of euros). Each bar represents a single economic sector. The analyzed period starts on the 8th of March, first day of lockdown, and ends at the mid of September, when all activities in Italy had been opened for one or two months. The most affected sectors, in absolute values, were: F (construction), G46 (wholesale trade excluding motor vehicles and motorcycles), C28 (manufacture of machinery and equipment), L68B (real estate activities excluding imputed rents), I (accommodation and food service activities), C25 (manufacture of fabricated metal products excluding machinery and equipment), C13-15 (manufacture of textiles, wearing apparel, leather, and related product). Thus, the most impacted activities were related to the accommodation, real estate, and manufacturing sectors. These results perfectly fit the Italian economy, mostly based on tourism and on small-medium enterprises (SMEs) related to the manufacturing sector (Malanima et al., 2010). Then, other sectors such as C24 and C29 (manufacture of basic metals and of motor vehicles, trailers, and semi-trailers, respectively), G47 (retail trade excluding motor vehicles and motorcycles), K64 (financial service activities), and R90-92 (creative, arts, and entertainment activities) have been also strongly impacted. Thus, the retail, financial services, and entertainment industry sectors also account among the most affected ones.

It is interesting to compare the economic losses in figure 8.21 with the most closed sectors (figure 8.20). In fact, the largest economic losses are those of construction (sector F), which was not completely closed (although the construction of private dwelling was blocked, that of highways, the public energy, water, transport utilities, as well as electrical and water-related works were never stopped). Other large economic losses were caused to sectors G46 (wholesale trade, except of motor vehicles and motorcycles) and C28 (manufacture of machinery and equipment), which represent an intermediate situation of sectors only partially closed (more than the 50% of the related activities) from the 23rd of March to the 14th of April. The losses related to sectors R90-92 (sport activities) and R93 (entertainment) display a completely different behavior. As mentioned previously, these were the sectors most notably affected by the Italian DPCMs in terms of closing days and limitations; however, their economic losses are limited. Sector L68B (real estate activities excluding imputed rents[3]), which was closed only from the 23rd of March to the 14th of April, suffered of an enormous economic loss, especially if compared with the short period of inactivity. Sector I (accommodation and food services) also suffered important economic losses, although in this case the result may be overestimated because delivery, take-away, and other business strategies could not be taken into account within this model. Note that the production of sector U (Activities of extraterritorial organizations and bodies) is 0 because of not belonging to the country, and thus its losses are also 0.

Reduced air emissions. Finally, figure 8.22 shows the reduced GHG emissions due to the reduced operation of the sectors. The error bars refer to the industry resilience $k_{min} = 0.1$ and $k_{max} = 0.3$. Most of the avoided emissions correspond to sectors D (electricity, as, steam and air conditioning supply), C23 (manufacture of other non-metallic mineral products), C24 (Manufacture of basic metals), E37-39 (sewerage, waste management, remediation activities), and A01 (crop and animal production, hunting and related service activities). Other large contributions come from sectors G46 (wholesale

[3] According to Eurostat (2013, p.7) *"imputed rents reflect the economic benefits of owner-occupied and social housing"*.

trade, except of motor vehicles and motorcycles), C20 (manufacture of chemicals and chemical product), B (Mining and quarrying), H49 (Land transport and transport via pipeline[4]), and C19 (Manufacture of coke and refined petroleum product). Thus, the greatest contributors to air emission reduction belong to groups C (manufacturing activities), G (wholesale and retail), and H (essential services' transport). The avoided emissions of all other sectors are negligible.

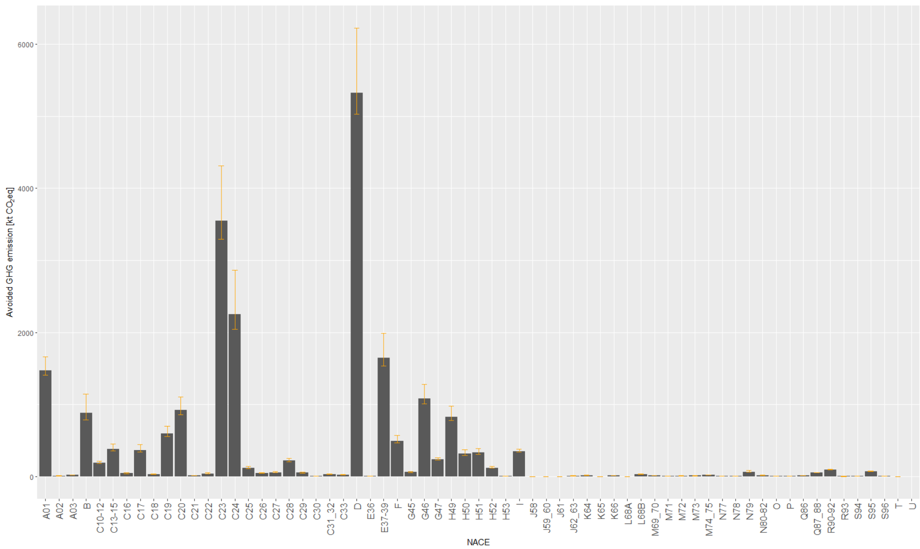


Figure 8.22: Greenhouse gases emissions reduction per sector. Effect due to the lockdown measures and inoperability of the sectors.

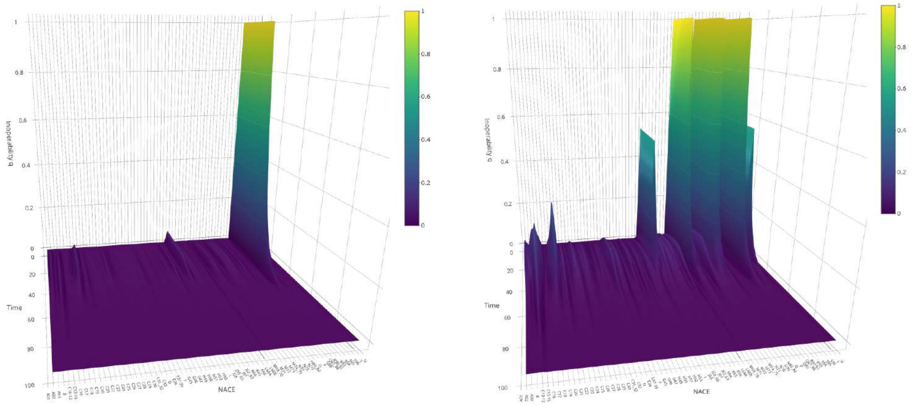
The ranking that emerges from this analysis is again completely different from the one of the most economically affected sectors. Indeed, when looking at the avoided GHG emissions, the main contributor was the D sector, i.e., that of electricity. This can be understood by looking at the interdependence of the D sector from group C (figure 8.18), which was one of the most affected by the lockdown measures. In general, the avoided emissions mainly reflect the intensities of the absolute emissions before the lockdown. In fact, in normal operation, the main responsible of GHG emissions are sectors D, A01, C23, E37-39, C19, H49, and C24.

Scenario analysis

Finally, according to the restrictive measures imposed during the period March-June 2020, five scenarios for the future of the Italian economy are here presented. The specific restriction adopted in the five scenarios are shown in table 8.13, and the values of q, are listed in Appendix A.6, Table A.9. Figures 8.23a and 8.23b show the dynamics of the inoperability for all sectors in scenarios 2 and 4, respectively, through a period of 100

[4]It includes passenger and freight rail transport, as well as taxi operation and public urban and suburban passenger land transport.

days. It is assumed that the restrictions are imposed for 30 days, after which the recovery of the economic sectors is calculated for 70 days. The full evolution of the 5 scenarios is available in section A.7.1 of the Appendix.



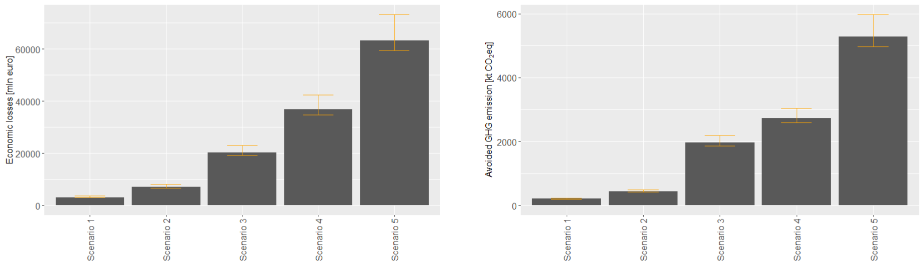
(a) Scenario 2 (b) Scenario 4

Figure 8.23: Inoperability dynamics for future scenarios. The restrictions are simulated to be imposed for the first 30 days and the simulation run for a period of 100 days.

The cumulative economic losses and GHG emissions reduction of all sectors have been calculated for the five scenarios and are shown in figure 8.24a. The error bars refer to the k_{min} and k_{max} values of the industry resilience, as previously discussed. In the first two scenarios, in which only entertainment and sports activities are affected, the impact on the economy and GHG emissions reduction is relatively low, although representing already 7 billion euros in scenario 2. The first measures which start to notably impact the economy are those included in scenario 3, i.e., when including the food and accommodation sectors, which have a high interdependence with other activities. In fact, the losses are larger than those of scenario 2 by a factor of 3, and the avoided GHG emissions are as high as $2000ktCO_2eq$. However, the highest impact is given by introducing restrictions on the mobility, which nearly double the economic losses with respect to scenario 3 because of the increased inoperability caused to all other sectors, as seen in figure 8.23b. In the model, the losses are closed to 40 billion euros. On the contrary, the avoided GHG emissions are not strongly affected by restrictions in scenario 4. The further closure of shops, commercial centers, and retail and trade activities in scenario 5 brought the total economic losses over 60 billion euros and the avoided emissions to more than $5000ktCO_2eq$. Thus, these data can be used in combination with epidemiogical models to predict the effects of increasingly restrictive measures not only on the spread of the virus, but also on the national economy.

Limitations and further improvements

Despite the relevance of the results in terms of policy prediction as well as assessment of the economic losses and air emissions reductions, the presented model has several



(a) Economic losses (b) GHG air emissions

Figure 8.24: Total economic losses and GHG emissions reduction. (a) Total economic losses and (b) GHG emissions reduction of the five simulated scenarios during a period of 100 days with restrictions running for 30 days.

limitations, especially in terms of accuracy and resolution.

First, the general limitations that are common to the input-output analysis also apply to the current model. Being a macro statistical model, it cannot take into account sub-national analysis, e.g., at regional or city level, because of the lack of available data. Moreover, the data ("naio_10_cp1700" database) (EUROSTAT, 2020e) provided by the EUROSTAT for Italy, as well as for many other countries (EUROSTAT, 2020d), are not related to the current year but to 2015 . This limitation could be overcome by using the supply-and-use tables provided by the Eurostat and computing the symmetrical IOTs from more up-to-date data for certain countries ("naio_10_cp15" database) (EUROSTAT, 2020c).

Second, a limitation is given by the minimum q_i value assigned to some sectors. Indeed, q_{min} was set equal to 1 when all activities in a sector were closed by a DPCM. Different 'workaround' strategies adopted by restricted sectors, such as take-away and food delivery for sector S96, or online services, were not taken into account. Other approximations have been adopted. For instance, DPCM March 9th 2020 closed large commercial shopping centers and stores during holidays and days before holidays. This condition has not been modeled, and full activity has been assumed. Regarding the business interruptions of DPCM March 22nd 2020, continuous production cycle lines whose interruption would have undermined the entire plant were allowed to operate (prior notice to local authorities). This, again, has not been taken into account because of the lack of data, and the corresponding sectors were modeled as closed. Finally, it is worth highlighting two aspects related to food service activities. First, DPCM March 9th 2020 introduced opening hours restrictions (no activity was allowed later than 6.00PM); second, in the closing period (after DPCM March 11th) all restaurants were entitled to work with home delivery, regardless of their previous license. Because of the difficulty of quantifying objectively and reasonably the impacts related to these measures, different simplifications were adopted: in the former case, the restaurants were considered fully operational; in the latter one, only those activities licensed to operate exclusively as take-away (subject of a specific ATECO code) were assumed to be running their business, while restaurants and others were considered closed. In any case, the golden rule was to follow the national DPCM as-is.

Third, in some cases, setting $q_{min} = 1$ results in overestimating the impact of the DPCM. Similarly, for partially closed economic sectors, the value of q_{min} obtained by weighting the closed and open subsectors was set as the minimum value for subsequent steps. This means that possible improvements of the open subsectors with respect to their pre-lockdown production was not taken into account. In other words, the open subsectors cannot compensate the closed subsectors. Indeed, the increase of production can only be modeled through the industry resilience k. Government funding, for instance, can boost the decay of the inoperability to its final value (the final demand) once a sector is declared operative. Thus, the sensitivity analysis for different values of k ($k = 0.1, 0.2, 0.3$) has been conducted because of the difficulty to precisely model the last Italian DPCM, i.e. that introducing public funding for a few billions of euros to enterprises and citizens. The value of $k = 0.3$ simulates a very fast decay rate (sectors recover in few weeks), whereas $k = 0.1$ represents a slow one (economic sectors recover in a few months).

Fourth, a limitation in the estimate of the air emissions reduction is due to the EUROSTAT dataset. Indeed, sector L68B (real estate activities excluding imputed rents) was not considered in the computation because there is no direct correspondence within the "env_ac_ainah_r2" EUROSTAT database (EUROSTAT, 2020a).

Finally, in this analysis no final demand reduction has been considered. Perhaps, this is the most critical limitation. Indeed, this analysis assumes a constant final demand (in this case, the initial demand before the lockdown) as a simplified hypothesis, similar to the initial report by Haimes et al. (2005a). A more precise analysis should update the final demand at each step, taking into account the (notable) economic losses and translating them into a reduction of i) salary, and ii) final demand.

Beyond the current limitations, further improvements should be developed, in terms of accuracy and connection with other real-time datasets. First, to verify their accuracy, the simulated results need to be compared with official statistics, when these will be released by e.g. the Italian National Institute of Statistics (ISTAT). We note, for now, that the reduction of CO, CH_4, and CO_2 emissions from fossil fuels and biofuels (35.2, 23.8, 26.0, and 15.7%, respectively) computed through our model for the industry sectors (group C and sectors B and F) are in good qualitative agreement with those of the dataset computed by the Copernicus Atmosphere Monitoring Service for the same period using real data (26.8, 19.6, 24.4, and 17.9%, respectively) (Guevara et al., 2020). Second, the simulated scenarios are built upon the current restrictions adopted in European countries rather than on epidemiological data. Future studies should strictly tie incremental restrictions with data on the daily number of infected people, available beds in public hospitals, and relevant epidemiological data in order to have a complete monitoring tool for policy-makers. Third, as suggested by Lian et al. (2006), a multiobjective formulation should be implemented to optimize future policies in terms of economy, COVID-19 diffusion, and air emissions reduction simultaneously. Fourth, other air pollutants such as acidifying gases, tropospheric ozone precursors, or particulate matter, may be taken into account. Finally, future studies and policy scenarios should also take into account the psychological implications of certain strategies in order to avoid political decisions based only on economical reasons. Indeed, the positive effects of physical (Maugeri et al., 2020) and cultural (Restubog et al., 2020) activities on psychological health have been widely reported. Future models and strategies should balance economic losses, psychological long-term effects, and the diffusion of the COVID-19 to avoid shortsighted policies.

8.3.4 Conclusion

In this study, the impact of the COVID-19 on the Italian economy has been analyzed in detail through the use of the inoperability methodology and the input-output tables. First, all the laws and restrictions adopted by the Italian government in the period March-June 2020 have been identified, pointing out the economic sectors affected by each measure. Second, the economic losses and the greenhouse gases emission reduction have been quantified by analyzing the period from March 8th (first day of restrictions) to mid-September 2020. Third, five scenarios have been discussed to predict the impact of the second wave. The simulated scenarios represent incremental restrictions that affect only some sectors: 1) sports, 2) sports and entertainment, 3) sports, entertainment, and food and accommodation, 4) those of scenario 3 and mobility, 5) those of scenario 4 and retail shops.

The simulation shows that, in Italy, the most affected sectors during the first wave in terms of inoperability, were R93 (sports activities, amusement, and recreation activities), R90-92 (creative, arts, and entertainment activities), and B (mining and quarrying). While sectors R93 and R90-92 were closed by national decrees, sector B was open but it suffered by its dependence from other sectors. With respect to the economic losses, the most impacted sectors were F (construction), G46 (wholesale trade, except for motor vehicles and motorcycles), and C28 (manufacture of machinery and equipment), whereas most saved GHG emissions were attributed to D (electricity, as, steam and air conditioning supply), C23 (manufacture of other non-metallic), and C24 (manufacture of basic metals) sectors.

The scenario analysis shows that the impacts on the national economy are limited before restricting the food and accommodation sector (from scenario 3), although representing approximately 20 billion euros. This is because those economic sectors not directly affected by restrictions are not strongly impacted as a consequence of the limited interconnections to the closed sectors. In scenarios 4 (reduced mobility) and 5 (reduced mobility and closed retail shops), instead, the restrictions influence many other economic sectors, even when not directly targeted by the restrictions. This is mainly due to the dense interconnections among tourism, manufacture and other industrial sectors. For instance, the closure of retail shops strongly affects many manufacturing sectors. The total economic losses for the five scenarios range from 3.6 billion euros for scenario 1 to over 60 billion euros for scenario 5.

Further studies are needed to relate the economic losses with the air emission reduction, social impact, and diffusion of the COVID-19. Indeed, wise and long-term policies cannot only take into account economic losses, as it occurred and is currently occurring in Italy, where the cultural sector has been completely closed. Instead, the sociological and psychological impact of banning the access to museums, galleries, concerts, and sport activities has to be considered. Using epidemiological and economic models and simultaneously considering the social effects of the restrictions, other strategies may be adopted in the future, following the example of other countries such as Spain, where the access to museums and cultural places was limited to a maximum occupancy rather than forbidden.

8.4 Concluding Remarks

In this chapter, three simple examples have been described based on three different methodologies - 1) a life cycle assessment, 2) a circularity indicator, and 3) an input-output analysis - related to three different sectors and three different scales - 1) a comparative study between reusable and single-use cups (at product level), 2) an environmental assessment of seven buildings by computing the embodied energy and carbon of materials (at supply chain level), and 3) an economic and environmental assessment of the impact of the restrictions due to the COVID-19 pandemia (at national level). All the three adopted methodologies present pros and cons.

First, the comparative LCA studies are useful studies to evaluate if a process, or a product, is better than another one in terms of several impact categories - in the case considered, seven impact categories have been evaluated - but findings are hard to be generalized. Moreover, as pointed out in chapter 7, bottom-up LCA studies evaluate single case studies, with consequent lack of generality. Typically, the chosen functional unit may consist of a single-use but no standard exists. As a consequence, the majority of the case studies took more complex functional units - e.g. serving 100 liters of beer at small and large events (A. Vercalsteren et al., 2010) - affecting the comparison with other studies. Indeed, specific hypotheses and underlying data allow to conduct useful comparative studies for private companies or public administration and to achieve worthwhile findings but they do not allow an easy comparison of results. Moreover, the lack of a (global) reference system affects the possibility of generalizing results on a global scale.

Second, the two described circularity indicators, i.e. the Building Circularity Indicator and the Predictive Building Circularity Indicator, have been proven to be a useful tool for policy- and decision-makers in order to compare different buildings in terms of circularity potential, since the indicators are properly normalized between 0 and 1 and they do not depend on the size of the building, but they cannot give any insight at national or international level to evaluate if all humanity may live in the *safe and just space*. To face such issue, one should consider the total of embodied emissions, for instance, and generalize the results at a global scale (although with a large error due to differences in construction approaches in different countries) by estimating the global emission necessary to provide a house to every person in the world, as advanced in chapter 1 through the discussion of Rovers (2019). The assessment of the design criteria, in particular of the design for disassembly criteria, allows to estimate the recovering potential of components and sub-components. Such approach, within the circular economy framework should be the starting point, a *conditio sine qua non*, for a proper evaluation of circularity. Indeed, it has been proven as it is possible, by weighting the embodied energy and carbon of materials by using the DfD criteria, to have a rough estimation of future recovery of materials and the corresponding impact in terms of mass, embodied energy or carbon. Straightforwardly, the same procedure can be applied to every impact category.

Third, the input-output model shows how the input-output tables can be easily used to evaluate the economic and environmental impacts of a change of the activity of a particular sector within a national economy. Although the IOTs provide rough results which cannot be considered satisfactory at a production process level, they allow, first, to expand the boundaries of very focused and limited LCA analyses, and, second, to easily evaluate the economic, and even the social (e.g. employment/unemployment), impact on the society. Finally, as shown in this chapter, dynamical simulations, as the inoperability model, provide an easy tool to evaluate the dynamics of future scenarios.

Concluding, the three examples show how none of the current methodologies, if taken individually, allows a proper circularity assessment as emerged from chapter 6 from underlying concepts and previous schools of thought, i.e. assessing a product/process within the planetary boundaries and with respect to the assimilative capacity of the environment. By the way, each methodology presents some features to be exploited in order to do such an assessment. For this purpose, LCA may provide the way to evaluate the different impact categories, the design criteria the procedure to evaluate the recovering potential, while the IOT the tool to evaluate the economic impact at international scale.

In next chapter the basic properties that an Information System needs in order to evaluate a circular thing are presented according to the Information System Design Theory.

9. Circular thinking

A circular transition is nowadays more necessary than ever. However, circularity and closing the loop do not necessarily mean and imply either a better environmental performance or to balance the human pressure to Nature with the assimilative capacity of the Planet. For this purpose, in previous chapters the state of the art related to environmental and circularity assessment has been discussed in detail. Before we proceed in defining what a circular thing is and how it should be defined, a brief wrap up of the main discussed concepts and topics is necessary. Table 9.1 summarizes the main qualitative answers to the research questions pointed out in Table 1 in the initial summary.

In part I, an interpretative framework - energy, material, information - has been introduced in chapter 1. From chapter 2 emerged that the increase of energy consumption may be entirely satisfied by renewable energy production, although the energy transition will still need a few decades and a wise management of the needed raw materials in terms of embodied impacts. Thus, in chapter 3, the depletion of raw materials in Nature is relevant only in the long-term, while in the short-medium term the urgency is due to the embodied impacts of materials (e.g. GHG emissions) and geopolical risks, as the current debate about the criticality material indices highlighted. Finally, chapter 4 pointed out how open, transparent, and complete *information* are necessary to manage a long-enduring common-pool resource Ostrom (1990). The CPR must refer to commodities (*Circular Commons*) and not to raw materials.

In part II, in chapters 5 and 6, the concepts and schools of thought inherited by the CE have been discussed in detail. Table 6.8 and Figure 6.8 summarizes the previous

Table 9.1: Main features emerged from each chapter

Chapter	Outcome
1. House on fire	Enegy-Materials-Information interpretative framework
2. Energy	Renewable energy may satisfy entirely the total demand.
3. Materials	Material depletion is relevant only in the long-term. In the short-medium term the crucial aspects are related to the environmental impacts and geopolitical risks.
4. Information	Need of perfect information, openness and transparency to manage a long-enduring Common-Pool Resources (CPR). The CPR must refer to commodities (Circular Commons) and not to raw materials.
5. An emerging paradigm	Currently the circular economy is acting as an umbrella concept.
6. The circular economy	See table 6.8 for inherited concepts.
7. How to assess circularity	Main tools: LCA, IOT, SD, CI/MFA, DfX.
8. Applications	There are no tools that can be applied to different levels. Need of mixing different methodologies (e.g. DfX ->IOT/LCA ->SD)

relevant aspects and concepts necessary to define an IS artifact for CE, and in particular its fundamental units (physiological needs of people, embodied environmental impacts of materials, design criteria, time), boundaries (planetary boundaries), interactions laws (feedback loops, natural biogeochemical cycles, population dynamics), and the system states (reference system from regenerative design).

Finally, in chapters 7 and 8 limitations and advantages of the most spread methodologies and tools for circularity (LCA, DfX, CI, IOT, SD, ..) are introduced. What emerged is that there are no tools that can be applied to different levels; hence, it is necessary to mix different methodologies and tools. In order to design a Theory, as illustrated by the Information System Design Theory (Gregor et al., 2007), the assessment methodologies and tools are fundamental in order to implement and instantiate an IS and validate it. On the other side, the system dynamics is necessary to study the law of interactions, while the products' properties are necessary to define the purpose and scope, as well as the constructs of an IS.

Thus, in this chapter, we will discuss how to define a *Circular Thing*, based on the ISDT. To design a meaningful new Information System artifact is necessary to define eight main components, previously described in section 5.5 in chapter 5, which will briefly reported here: 1) Purpose and scope, 2) Constructs, 3) Principles of form and fuctions, 4) Artifact mutability, 5) Testable propositions, 6) Justificatory knowledge, 7) Principle of implementation, and 8) Expository Instantiation. Focus 9.1 explains a brief example regarding how to define an IS artifact related to the definition of an Information System to evaluate the interdisciplinarity in research for Higher Education Instutions regarding the Sustainable Development Goals.

Focus 9.1 — Example of Information System artifact definition. This example and the text of this focus is largely based on or adapted from the work "Sustainable

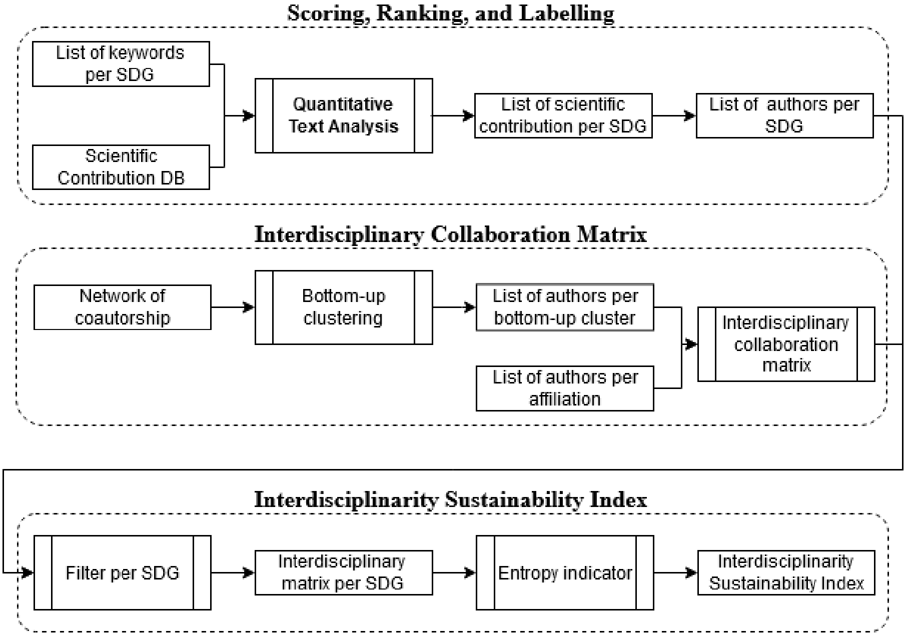


Figure 9.1: Flowchart of IS artifact to measure interdisciplinarity in research.

Development Goals research in Higher Education Institutions: an interdisciplinarity assessment through the design and testing of an entropy-based indicator" (Dario Cottafava, Ascione, Corazza, et al., 2021). Since 2015, the United Nations are invoking Higher Education Institutions (HEIs) to adopt an interdisciplinary approach to SDGs, that is to say that universities are encouraged to overcome one single discipline perspective in dealing with sustainable development issues. Subsequently, sustainability scientists have demonstrated how SDGs are interconnected and interdependent. This example is focused on the importance of driving the scientific production of a HEI towards SDGs as a concrete institutional contribution to sustainable development. While nowadays bibliometric tools for SDGs are emerging, all those models are not focused on rewarding interdisciplinarity or to be used as a decision-management tool to drive SDGs-related research at a micro-scale (institutional level). This example proposes a novel multi-step methodology, applying Information System Design Theory (ISDT) to map and assess interdisciplinary research for each SDG and it applies it in the context of an Italian university (University of Turin), as a first experiment. A database with more than 30,000 entries representing the SDG-related scientific production from 2015 to 2019 is analyzed through a Quantitative Text Analysis. Afterwards, interdisciplinarity, intended as a collaboration among researchers in diverse disciplines, is measured for each SDG through a Social Network Analysis (SNA) of co-authorships. Bottom-up clusters of researchers belonging to diverse departments are selected through the modularity algorithm (Blondel et al., 2008; Brandes et al., 2008). Lastly, the identified clusters are analyzed proposing an Interdisciplinarity Sustainability Index (ISI).

In this example, we define an Information System (IS) artifact (Gregor et al., 2007), in particular a design method, to support the governance of HEIs to evaluate, timely monitor, and analyze the interdisciplinarity in academic research collaborations within a particular theme/field (e.g. within the framework of the SDGs), which allows to evaluate the overall performance of an institution as well as to identify and evaluate single groups of researchers. To evaluate the interdisciplinarity, we adopt a spatial approach (Garfield et al., 1978) focusing on a single object (in our case the author). The full declaration of the eight components required for the Information System (IS) design method are presented in the Table 9.2. Figure 9.1 shows the overall flowchart and the three main blocks of the proposed methodology to build an Interdisciplinarity Sustainability Index. The implementation of the IS method consists of three main processes: 1) a Scoring, Ranking and Labelling process, 2) the construction of an Interdisciplinary Collaboration Matrix, and 3) the evaluation of an Interdisciplinarity Sustainability Index. Finally, the design method has been instantiated and tested on a first experiment, i.e. the University of Turin research production related to the 17 SDGs, in order to validate its robustness in terms of change in interdisciplinarity indicators, fields/themes, recognizable clusters' sizes, or institutions analyzed. Precise results and findings, in terms of research production of the University of Turin related to the 17 SDGs, as well as the details of the adopted methodology, are fully reported in Dario Cottafava, Ascione, Corazza, et al. (2021). ■

9.1 Defining a *Circular Artifact*

To conclude our discussion, which started from the definitions of the CE (see chapter 5) and from previous schools of thought (see chapter 6), let's define what a *circular artifact* is and how it should look like. To do so, I follow the approach of Gregor et al. (2007) based on ISDT. Since nowadays no clear and recognized standard exists related to the circular economy, the definitions provided in this section are intentionally general and broad, in order to set the fundamental properties of a *Circular Thing* meanwhile allowing future researchers and practitioners to develop their own approach. In IS design theory, according to Walls et al. (1992) an artifact is constructed as a test of a design theory and the last two points - i.e. principles of implementation, and expository instantiation - are intended as additional components and thus not compulsory to define an IS artifact.

9.1.1 Purpose and scope

The purpose and scope define *"what the system is for"* (Gregor et al., 2007). This feature includes the functional units, the boundaries of the system or of the theory, as well as its aim and purpose.

For this purpose, relying on all previous chapters' discussions and, in particular, how discussed in chapter 4 in section 4.2 where the *Circular Commons* have been briefly

Table 9.2: Example of definition for an IS artifact. The example is related to the assessment of interdisciplinarity in research regarding the Sustainable Development Goals.

n°	Component Type	Description
1	Purpose and scope (the causa finalis)	The aim is to develop an IS tool to support the governance of Higher Education Institutions to evaluate, timely monitor, and analyze the interdisciplinarity in academic research collaborations within a particular theme/field (e.g. within the framework of the Sustainable Development Goals), which allows evaluating the overall performance of an institution as well as to identify single groups of researchers. The boundary of the analyzed system is the scientific production (papers, chapters, book chapters, in proceedings, ..) of the target institution.
2	Constructs (the causa materialis)	The basic entities are: scientific contributions (e.g. papers, books, ..), authors (researchers, professors) and affiliations (e.g. departments), collaborations (e.g. co-authorships), theme/field keywords (e.g. SDG).
3	Principles of form and function (the causa formalis)	An ISI should evaluate the interdisciplinarity of collaborations of an HEI for a theme/field for emerging bottom-up clusters of different sizes (from a single researcher group up to the size of departments).
4	Artifact mutability	The artifact may be adapted for any HEI with precise departments subdivision and for any field/theme that needs to be studied. There exist no limits nor on which, or how many, departments the HEI can have neither on which, or how many, fields/themes are the object of the study.
5	Testable propositions	The artifact should be robust to change in interdisciplinarity indicators, fields, clusters' sizes, or institutions analyzed.
6	Justificatory knowledge	The artifact derives from previous interdisciplinarity indices (Stirling, 2007) and relative discussions. The relevance of interdisciplinarity in education, research, and innovation is common knowledge (Gibbons, 1994; Ledford, 2015)
		Additional components
7	Principles of implementation (the causa efficiens)	The overall process may consist, at least, of three sub-processes: 1) labelling scientific contributions and authors (ranking process), 2) unveiling emerging clusters of authors (interdisciplinarity matrix), and 3) evaluating of the interdisciplinarity. The specific process for the instantiation is shown in detail in Figure 9.1 in the main document.
8	Expository instantiation	A first experiment has been tested on the DB of the University of Turin by evaluating the 17 SDGs (17 different fields/themes), for the 27 departments. The robustness to index change has been tested by discussing two different interdisciplinarity indicators. Although no test has been conducted on different institutions or clusters' size, the former can be deducted from the basic units and boundaries defined (if an institution has a department subdivision, then it is possible to give affiliation to authors, a condition necessary to evaluate the interdisciplinarity), while the latter simply depends on the used clustering algorithm and its resolution.

defined starting from the work of Ostrom (1990), the goal of a circular artifact is to, first, *indefinitely-last* and, second, to fulfil a precise function, e.g. an house should provide a safe shelter for a person (see section 7.4 in chapter 7). As previously discussed, an object to last forever needs to be bounded within a *reference system*, i.e. the planetary boundaries or the local system capacity. To allow such evaluation, every circular object should be evaluated in terms of embodied impacts (e.g. embodied energy or carbon) due to its life cycle and then assessed in terms of percentage of the yearly assimilative capacity, or regeneration rate of the Planet. Finally, every object obviously cannot last forever for itself, but it should be reused, repaired, remanufactured or recycled. Thus, to evaluate these features, the average lifespan of each object and the potentiality to be recovered are necessary information. The recovering potential mainly depends on the design criteria, in particular the Design for Disassembly criteria (when referring to "physical" products, thus for chemical products, or processes other kinds of logic are necessary), which permit to evaluate the potentiality to recover an object in order to maintain its functionalities. The main elementary features here described are summarized in Table 9.3.

Table 9.3: Purpose and scope of a Circular Thing.

Purpose and Scope		
Feature	**Definition**	**General Description and examples**
Aims	The aim of a Circular Thing is to indefinitely-last (the object itself or its future transformation) providing its functionalities to every people who needs it lying within the local or planetary boundaries.	A) Lying within PB or local environmental capacity: % of the maximum capacity of the environment (See section 6.2) B) Function of the product (See section 7.4). E.g. provide a shelter to a family, accessibility to the internet, ...
Boundaries	The boundaries of a Circular Thing are the Planetary Boundaries, or the local environmental capacity depending on the impact category.	A) Planetary boundaries: maximum amount of impact which can be absorbed by the global environment (See section 6.2). E.g. Embodied carbon B) Local-Regional environmental capacity: maximum amount of impact which can be absorbed by the local environment. E.g. eutrophication (both local and planetary)

Thus, a *Circular Thing* basically should be evaluated in terms of the planetary boundaries in order to know the percentage of, for instance, the total amount of carbon dioxide emissions the life cycle of the analyzed *Thing* implies. The percentage has to be evaluated not only for the production, use and disposal of a single *thing*, but it has to be evaluated for millions, or billions of copies, in order to provide the object to every person who needs it. Such aim, although theoretically trivial - indeed it simply consists in multiplying the impacts generated by the life cycle of a single object by the total market size (in the case of *optional* things), or by the total global population (in the case of basic human needs, e.g. a shelter) and then by normalizing the total impact with respect to the planetary boundaries - it is not simple at all and the definition is not yet complete and satisfactory. Indeed, does this simple computation allow to know if humanity will be able to lie within the planetary boundaries forever? No. Let's imagine to produce several commodities for all the population. It could happen that the first N commodities already fulfil the total amount of carbon dioxide the Planet can absorb yearly. Thus, what about the subsequent commodities that will be produced? Who has the right to produce a commodity and impact on the environment? Which are the priorities for humanity? I think, everyone can agree that the basic human needs have the priority. Well, and then? Does the humanity allow to produce beer or wine, corn or rice, paper book or ebook? In such comparisons, comparative LCA may support the decision-makers to say a product is better than another one, but nothing can be stated about the human/consumer preferences and utilities. Obviously, such reductionist approach cannot work. Concluding, on top of these considerations a *global Circular Information System* is necessary to evaluate a *Circular Thing*. In other words, nothing can be evaluated alone; rather every thing produced, used, or disposed, should exist and can be defined if and only if it is defined together with every other *thing* on the Planet, i.e. as a unique entity. A reader can notice similarities with the idea of the *Zoe* of the Posthuman theory (Braidotti, 2013), the idea of Nature in Biomimicry (Benyus, 1997), or the encyclical *Laudato Si* of Pope Francis (Pope Francis, 2015). Finally, we are able to give a precise definition of a circular thing, which directly emerges from the purpose and scope of the work in progress theory. A very general and broad definition, considering natural and artificial processes at the same level, could be:

Definition 9.1.1 — Natural Circular Thing. A *Natural Circular Thing* is a unique entity composed by every transformation process which occurs on Earth allowing the Planet to lie and rest forever within the Planetary Boundaries (i.e. within the Holocene) and to satisfy the needs of every living beings.

Such a general definition, nowadays, cannot be assessed and thus an Information System cannot be defined. A more strict definition, relating only to human processes and activities, could be:

Definition 9.1.2 — Artificial Circular Thing. An Artificial Circular Thing is the set of all human activities which must indefinitely-last fulfilling all the needs of every people lying within the local or planetary boundaries.

In other words, with respect to a single product, object or process, recalling the aim defined in Table 9.3 one can define

Definition 9.1.3 — Circular Thing. A Circular Thing exists if and only if it is defined together with every other Thing (Artificial Thing set) and has to indefinitely-last (the object itself or its future transformation) providing its functionalities to every people who needs them lying within the local or planetary boundaries.

Concluding, for the sake of completeness and clarity, the Planetary Boundaries (Rockström, W. L. Steffen, et al., 2009) (see section 6.2) recently have been quantified in terms of life cycle impact categories by S. Sala et al. (2020) and may be simply used a global reference system. Table 9.4 shows some of the planetary boundaries with respect to the LCA impact categories as described by S. Sala et al. (2020).

9.1.2 Constructs

The constructs represent the functional units, the basic entities of a theory. Together with the purpose and scope, they define the fundamental feature of an IS artifact. As anticipated in the previous subsection, the functional units of a *Circular Thing* regard several basic aspects.

First, every *thing* is composed by one, or more, materials, which, mixed together through a transformation (physical, chemical, or mechanical), create sub-components, components or the final object itself. Every material, and subsequently every component, has to be defined in terms of its embodied impacts, e.g. embodied carbon or energy (G. P. Hammond et al., 2008), which is the fundamental elementary unit.

Table 9.4: Planetary Boundaries and LCA impact categories. Some of the planetary boundaries (PB) proposed by Rockström, W. L. Steffen, et al. (2009) as reported by S. Sala et al. (2020) for corresponding LCA impact categories. Adapted from S. Sala et al. (2020).

Impact category	**Acronym**	**Unit**	**PB**	**Ratio**[1]
Climate Change	CC	Gt $CO_{2,eq}$	6.81	0.86
Ozone Depletion	ODP	Mt CFC-11eq	0.539	0.01
Marine Eutrophication	MEU	Mt Neq	201	0.06
Freshwater Eutrophication	FEU	Mt Peq	5.81	0.09
Water Use	WU	km^3 world eq	182,000	0.03
Land Use	LU	Gt soil loss	12.7	0.001

[1] the ratio represents the percentage of the EU consumption over the Planetary Boundaries.

Second, the embodied impacts should be assessed with respect to the whole life cycle of the product. If, on one side, the extraction, production, and even the use phase, theoretically, could be evaluated with a certain precision (by knowing exactly the adopted transformation process), the same is not valid for the End of Life phase. Indeed, since it is not possible to know precisely the End of Life of a product, the EoL impacts should be necessarily evaluated only through the likelihood to recover the materials, the components or the product itself through reusing, repairing, remanufacturing or recycling. In fact, although it is possible to assess precisely the impact of a particular EoL strategy, currently it is not feasible to know precisely how many products will be repaired or recycled for instance. Thus, the recovering potential should be identified through the elementary Design for Disassembly properties of a product. According to G. Johansson (2008), for instance, every product has four fundamental properties, i.e. 1) the *ease of identification*, 2) the *accessibility*, 3) the *ease of separation*, and 4) the *ease of handling*. More in general, the recovering potential should be named regenerative potential by including Design for Adaptability, Flexibility or other criteria in order to also assess positive impact of a product/service. In terms of regenerative capacity, it is noteworthy to highlight how in the constructs, there is no clear component (except for the above mentioned design criteria). This aspect is due to the fact that the regenerative component is intrinsically defined with respect to the boundaries of the system. In other words, a single object can be considered regenerative if and only if it has direct positive impact on the environment. This obviously is not possible for all products / services but only for certain well-design products. On the contrary, evaluating the whole production of commodities with respect to the planetary boundaries and the regenerative capacity, it allows to define a regenerative *Artificial Circular Thing* (i.e. the set of all the human activities).

Third, as declared for the purpose and scope, the planetary, or the local, boundaries should be included in the definition to give the proper reference system to the embodied impacts. To evaluate the embodied impacts with respect to the boundaries, thus, it is necessary to know and define the lifespan of every components of a product, and the

Table 9.5: Constructs, i.e. elementary entities, a Circular Thing needs to be defined.

Constructs		
Feature	**General Description**	**Example**
Embodied Impacts	Embodied Impacts of materials	Embodied energy and carbon, acidification potential, biodiversity loss (See sec. 6.2, sec. 7.1, for theory, and chap. 8 for application)
	Embodied Impacts of components	Embodied energy and carbon, acidification potential, biodiversity loss (See sec. 6.2, sec. 7.1, for theory, and chap. 8 for application)
Recovering (Regenerative) potential	Design for disassembly (or flexibility, adaptability)	Connection type, connection accessibility, crossings, form containment (See section 8.2) Time for disassembly, composite materials, or ease of identification, accessibility, ease of separation, and of handling (See section 7.4)
Scalability to the boundaries	Quantity	Market size or total population will need such product (See section 4.2 for global population)
	Lifespan	Average lifespan of sub-components, components and/or products
Function	Product function	The product function is an un-mutable entity necessary to identify the quantity. It can fulfill basic human needs or optional ones. For instance, a house should be provided for the global population, a sailing boat only to the identified market size

lifespan of the whole product itself.

Finally, according to the product design theory (Hubka et al., 2012), the fundamental property of every object is to fulfil one, or more, precise functions. Table 9.5 summarizes the functional entities which should be considered to define a *Circular Thing*.

9.1.3 Principles of form and functions

The principles of form and functions define the structure and the functioning of an IS artifact. In other words, a blueprint or the general architecture should be declared at this phase (Gregor et al., 2007), including as defined by Dubin the laws of interactions of such system (Lynham, 2002).

Figure 9.2 shows the most elementary blocks an IS artifact needs to assess a *single* Circular Thing. Four main components, as described for the constructs subsection, i.e. 1) embodied impacts, 2) design criteria, 3) market size, and 4) planetary boundaries, act as input for a generic System Dynamics model which should evaluate the effects of feedback loops (reinforcing or balancing), due to the design criteria, by assessing the recovering potential and thus predicting future impacts of a product. The System Dynamics model should compute, roughly speaking, the percentage of the impacts over the yearly planetary boundaries.

Basically, the Macro aspects, i.e. the embodied impacts of materials and the planetary, or local, boundaries, together with the Micro aspects, i.e. the design criteria, should be evaluated through a SD model in order to evaluate the percentage of the generated impacts per year over the total allowed (according to the system boundaries). The embodied impacts may be evaluated by the using of 1) traditional Life Cycle Assessment tools (Guinée et al., 2011), 2) environmental extended Input-Output tables (CMU, 2018), or through ad hoc databases, as the Inventory of Carbon and Energy developed by G. P. Hammond et al. (2008).

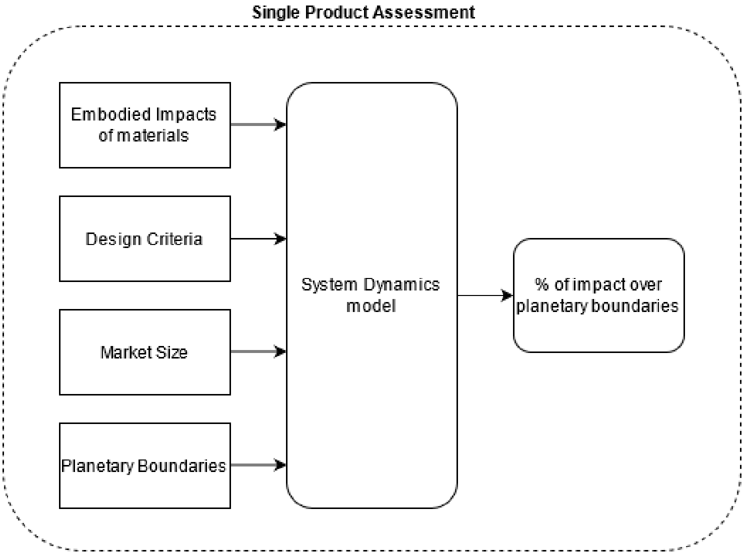


Figure 9.2: General flowchart to assess a *single* Circular Thing.

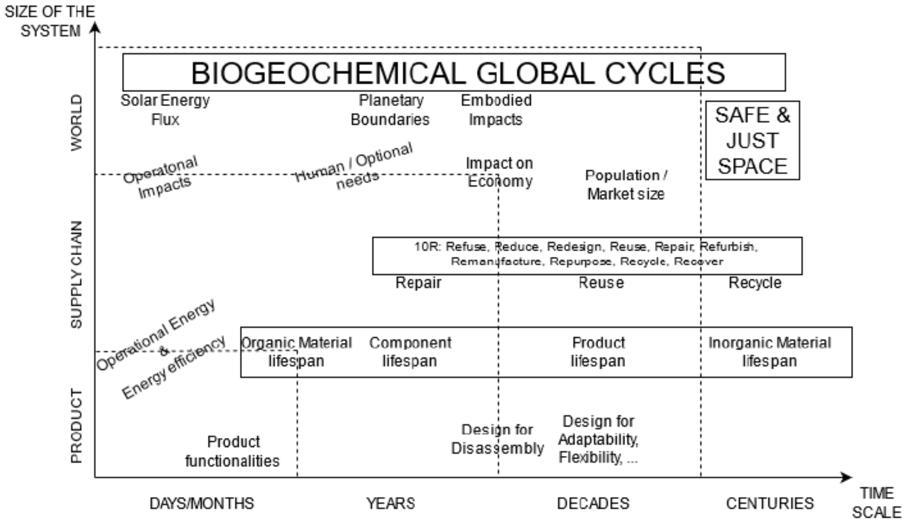


Figure 9.3: Time and spatial scale of the IS artifact. General components an IS artifact needs to assess a Circular Thing are represented.

Recalling the basic notions of system dynamics and the design process to identify all the relevant variables to build the causality diagram, as described in section 7.7 in chapter 7, Figure 9.3 summarizes the most general components such a model needs to take into account (still in a general formulation). The *time scale* varies from days/months to years/decades, or even centuries, depending on which aspect is considered, while the *size of the system* changes from the product level to the whole Planet (world level) passing through the supply chain scale. Basically, on a daily/monthly time scale the fundamental aspects to be taken into account regards the use phase of a product and its impact, i.e. the operational energy/impacts on the environment, and the product functionalities which fulfil a precise human need. On the other side, the operational energy, for instance, should be fulfilled by the daily solar energy flux from the sun, or by other renewable energy sources (e.g. wind, hydro, biomass, ...). On a months/years timescale, instead, the fundamental aspects are the organic material lifespan, as well as the subcomponents/components lifespan of products (at product and supply chain level), and the possibility to reuse, or repair, products. Repairing or reusing an object, which should be intended in its broadest meaning including remanufacturing and reconditioning for instance, mainly depends on the Design for Disassembly criteria. DfD criteria, indeed, represents the product properties to be recovered allowing to detach single components (selective disassembly), as well as to disassemble an entire product (complete disassembly). On a larger scale, i.e. at supply chain/world level, the main aspects are related to the human/optional needs to be fulfilled (depending on the product functionalities) and to the planetary boundaries. The planetary boundaries, in particular, represent the limit for the impacts generated yearly by the use phase (operational impacts) and by the production and EoL phases (embodied impacts) of the products. As described in chapter 6, the planetary boundaries (not all of them) are regulated by the biogeochemical local or global cycles, which may vary from a few days timescale up to several centuries. In-between the relevant features are the design for disassembly criteria (at product level), the impact on economy (at supply chain level), and the embodied impacts (at world level). These three elements affect each others, mainly depending on the lifespan. Indeed, the design for disassembly criteria affect the recovering potential of subcomponents/components of the analyzed products and thus the related embodied impacts generated. At the same time, repairing or reusing an object will affect a national, or the global, economy by changing the production of certain economic sectors, and, eventually, of every connected sectors. These interactions could be analyzed, for instance, thanks to the Input-Output tables (W. Leontief, 1986), or other macro-economic tools and methodologies. The embodied impacts, instead, both at supply chain (i.e. local level) or at world level, could depend on the impact category considered. At the decades time scale, the main driver to be taken into account is related to the global population (for basic human needs) or the market size (for optional needs). Obviously, the use phase depends on the population/market size aspect on a daily/monthly base but the population dynamic can be considered a slow varying variable (on a year/decade timescale). With regard the lifespan of components, products or materials, a brief explanation is necessary. In Figure 9.3, all lifespan variables lie between product and supply chain scale. This is to graphically show the interaction between the two spatial levels. Indeed, the different lifespans clearly represent a property at product level, but a change in the lifespan of components, products, or used materials directly affects the supply chain level, since national economic sectors have to adapt their production, and the world level, since the embodied impacts generated will change. Moreover, roughly speaking, the lifespan depends on which part of a product is considered. Organic material last from a few days up to years, product components may last several years, a product itself from a few years up to several decades, while inorganic materials theoretically last centuries. This last feature is the reason to put the recycling on a longer timescale with respect to reuse or repair. Finally, for the sake of clarity, the so-called *safe & just space* (Raworth, 2017), although it cannot be properly considered a variable of the system, lies on the top right part of the scheme, i.e. at centuries timescale and world level.

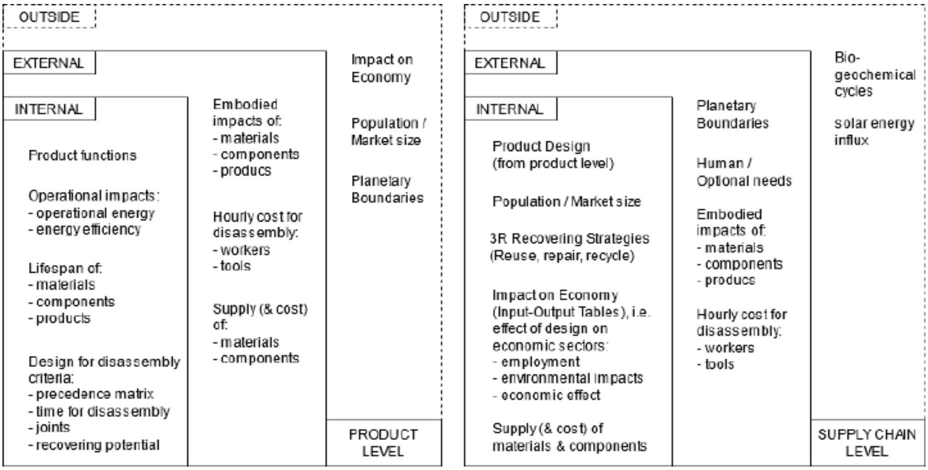


Figure 9.4: Product and Supply chain levels variable classification.

Following with the design process to define a System Dynamic model, a further classification to clarify the different aspects is shown in Figure 9.4 and 9.5 among *internal*, *external*, and *outside* (i.e. not considered) variables at product, supply chain, and world level. The internal ones represent the variables with change within the same level, the external ones, instead, include all variable not directly affected by the internal variables, i.e. the ones considered as external constant factors, and the outside variables are the ones which are not included within the specific level and have no impact.

In particular, Figure 9.4 shows the product (on the left side) and the supply chain (on the right side) levels, while Fig. 9.5 the relevant variables at the world level, including outcomes from lower levels. As previously exhibited in Figure 9.3, at product level, the internal variables are the product functions, the operational impacts, the lifespan of materials, components, and products, as well as the design for disassembly criteria, while the external ones are the embodied impacts (which refers to the supply chain or the world level), the hourly cost for disassembly (which can be considered constant as a first approximation) and the supply cost of materials or components. At product level, the impact on economy, as well as the global population / market size or the planet boundaries initially have no influence in the assessment (although in a complete model it is not completely true). On the other side, at supply chain level, the internal variables to be considered refer to the product design outcome (from the product level), the population / market size, the recovering strategies, the cost of materials / components, and finally the impact on the economic sectors, in terms of economic, environmental, or social effects. The external variables, in this case, include the planetary boundaries, which give the maximum amount of externalities which can be generated, the human / optional needs (which can be considered as the requirement to be fulfilled not influenced either by the product design or by other factors), the embodied impacts and the hourly cost for disassembly. Two variables are outside the boundaries of the supply chain level, i.e. the bio-geochemical cycles and the solar energy influx. Finally, Figure 9.5 shows a simplified representation of the variables at global level. In this case, the internal variables are the impacts generated by the products (from the product level) and by the economy (from the supply chain level), the planetary boundaries (which at a first approximation can be considered constant in time), the global population / market size, and the human / optional needs. The only external variables are the solar energy flux, the bio-geochemical cycles and the safe & just space. These last three variables can be considered as the only external variables, and, thus, that cannot be controlled by the system dynamics.

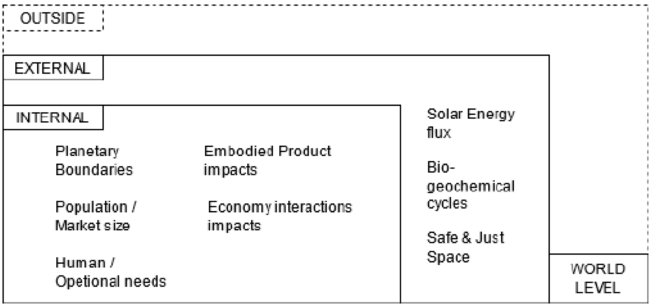


Figure 9.5: World level variables classification.

To conclude this first attempt to describe a holistic dynamic system to assess circularity a few clarifications are needed. Figure 9.3, 9.4, and 9.5 are certainly neither perfect nor exhaustive.

First, in Figure 9.3 several generalizations and approximations appear. About the time or spatial scale, some variables should be considered to lie not only within a precise box (e.g. years and supply chain) but on multiple levels. For instance, reuse may vary from days to decades or centuries, depending on the product considered. The same occurs for human / optional needs. Biogeochemical cycles, as described more in detail in section 6.2 in chapter 6, vary from local ecosystem to the entire Planet, depending on which cycle is considered. For instance, the carbon cycle can be considered only at global level, while the phosphorous cycle, since there is no gaseous form, it could be considered only locally (although Rockström, W. L. Steffen, et al. (2009) defined a related planetary boundary). And so on.

Second, Figure 9.4, and 9.5 should be read together and simultaneously. Indeed, as defined in section 9.1.1, a circular thing (i.e. the sum of all products) needs to be defined simultaneously from the product level up to the world level, considering its impact for centuries. In this sense, the design for disassembly criteria, for instance, should be evaluated recursively from the product level (amount of recovered materials/components) up to the world level (embodied impacts generated and percentage over the planetary boundaries) passing through the "collateral impacts" generated on the economy, due to a change in production for one, or more, economic sectors. Only such an assessment allows to evaluate if the global production of products to satisfy the human needs may last for centuries allowing the Planet to lie in the safe and just space.

Finally, all the figures reported in this section do not consider other possible relevant influencing factors, as the adoption rate of new products, the behavioural change effects of some products, or technology improvement, which may cause reinforcing/balancing feedback loops.

Concluding, the basic structure should consist in the modules represented in Figure 9.2, which may be simply divided as 1) input, embodied impacts, design criteria, market size, and planetary boundaries, 2) a system dynamic model which processes all interactions about the various input, and 3) output, i.e. the percentage of impacts with respect to the total amount allowed related to a certain impact category. Regarding the input and the model, for the sake of clarity, the components can be classified into a micro, meso and macro levels, similarly to what was done in the example in section 8.2, where, roughly speaking, the micro level refers to the property of products, i.e. the design aspects, the meso level to the supply chain or the interactions within an economy, and the macro level regards the most general aspects, i.e. the embodied impacts of materials and their positioning within the planetary boundaries. Table 9.6 summarizes the fundamental IS components and their classification into input/output, and micro, meso, macro level.

Table 9.6: IS component classifcation

IS component	**IS classification**	**Level**
Planetary Boundaries	Input	Macro
Market Size	Input	Macro
Design criteria	Input	Micro
Embodied impacts	Input	Macro
System Dynamics	Model	Meso
Percentage over PB	Output	Macro

To go further, the example 9.1 shows a simple flowchart by linking the different levels and underlining how they could interact and affect each other recursively.

■ **Example 9.1 — Designing of modules.** Starting from the variables and influencing factors described in this section a more detailed example could clarify some aspects. Figure 9.6 shows several modules which can be used to link the different levels in order to simulate the dynamics of the impacts including simple feedback loops and where an optimization process should act. In the representation, dashed lines represents generic feedback loops. Basically, a product should be evaluated considering the embodied impacts of materials, and their assemblage to components, and the whole product. Once evaluated the production process (the top dashed box), the operational impacts have to be taken into account as well. Then, thanks to the evaluation of the design criteria, the theoretical recovering potential can be quantified. The recovering potential, i.e. the likelihood for a product to be repaired, reused, or recycled (in general recovered), directly affects, in a reiterative process, the embodied impacts of materials, components and products (i.e. the EoL of the considered product) and the local, or global, economy by changing the production of economic sectors. To evaluate the total recovering potential of a certain product, the precise lifespan of the evaluated components / products is necessary. Consequently, the recovering potential, together with the total population, or the market size for that product, and the planetary boundaries are necessary to assess the impact on the local, or global, economy. The population / market size simply acts as a multiplicative factor, while the planetary boundaries act as a constraint, which theoretically cannot be overpassed. Finally, all impacts, i.e. embodied, operational, and from the economy, converge to compute the ratio over the total planetary boundaries. Thus, the ratio can be consequently used to optimize the management of the production, use, and disposal of every commodity in order to satisfy human, as well as the Planet, needs. ■

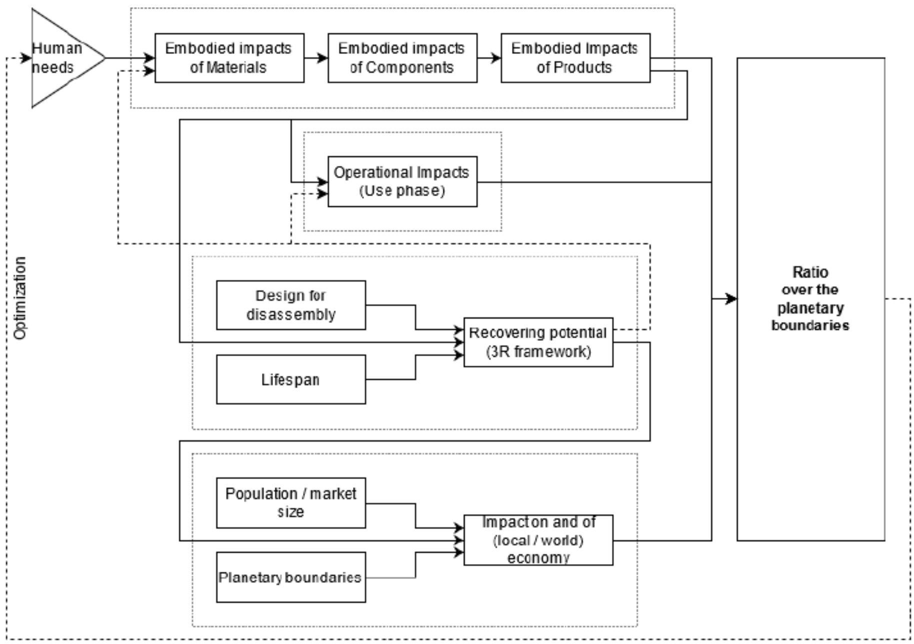


Figure 9.6: A multi-level flowchart of an IS artifact. It links product properties with the planetary boundaries and the impact of design criteria to the economy.

9.1.4 Artifact Mutability

The artifact mutability component refers to the system state and its eventual modifications. In other words, an IS artifact should account for flexibility, mutability and adaptability to future variations or improvement (Gregor et al., 2007). In IS, generally speaking, this aspect is the modularity of a software (Schwanke, 1991).

For this purpose, the input as defined in Figure 9.2 are totally interchangeable. Avoiding the yet unexplained and unexplored interactions among planetary boundaries (see section 6.2 in chapter 6), each embodied impact can be considered totally independent. Thus, an IS artifact could evaluate only one, or more, impact categories without affecting future analyses on other impact categories. Each planetary boundary can be assumed as a fixed quantity and independent from each other, as a first approximation.

Finally, the design criteria aim is twofold. On one side, they provide a generic weight on embodied impacts by evaluating the easiness of disassembly a product or a component without affecting other parts (see the example on the residential building in section 8.2 in chapter 8), and, on the other side, through the precedence matrix they can give a precise indication on the selective or complete disassembly (see section 7.4 in chapter 7). In any case, once assessed the embodied impacts of materials and per component of a product, the methodology still works without a precise design assessment. For instance, avoiding the evaluation of the design criteria, the subsequent system dynamic model will simplify only by considering the lifespan of the whole product.

Table 9.7: Testable propositions and their rationale.

Testable proposition	**Justification and rationale**
1. The artifact should be robust to change in any of its components	Indipendence of impact categories and planetary boundaries; external weighting process for design criteria
2. The artifact needs to allow the multiple assessments of several products and to forecast their potential simultaneous impacts on the environment	Additive properties of impacts.
3. The artifact needs to allow simulations to forecast the impacts in the future in order to correct eventually wrong decisions on global production.	This can be simply provided by the System Dynamics model and it is necessary to assess the impact on future generations.

9.1.5 Testable Propositions

The testable propositions are the truth statements to be validated. In other words, they need to provide the hypothesis to test and validate the IS artifact in order to give to it a verifiable and checkable rationale (Gregor et al., 2007). In this sense a few statements are fundamental to give the necessary robustness to it and to eventual modifications, as anticipated in the *artifact mutability* section. In particular, first, the artifact should be robust to change in the products evaluated, impact category and design criteria considered, as well as on future variations of market size and new improvement on planetary boundaries. As discussed in artifact mutability, the only element providing feedback loops are the design criteria, which in the limit of no assessment they should be simplified to the dispose of the whole product. Second, it needs to allow the multiple assessment of several products and to forecast their simultaneous potential impacts on the environment. This is simply given by the additive properties of the environmental impacts. Finally, the IS artifact needs to allow simulations to forecast the impacts in the future in order to correct eventual wrong decisions on global production. This aspect should be fulfilled by the System Dynamics model which, depending on its complexity, can be as accurate as collected data allow. Table 9.7 summarize the three propositions.

9.1.6 Justificatory Knowledge

The justificatory knowledge consists in all previous human knowledge necessary to explain the rationale of the theory. Throughout the whole document, the rationale of the principles here presented have been largely discussed for an IS artifact to evaluate and define a Circular Thing. Table 9.8 summarizes the main principles and the corresponding literature.

Table 9.8: Justificatory knowledge for each component of the IS artifact.

IS component	**Corresponding literature**
Planetary Boundaries	A. Original formulation (Rockström, W. L. Steffen, et al., 2009) B. LCA-PB (S. Sala et al., 2020) C. Safe and just space (Raworth, 2017)
Market Size	A. Global population: (Paul R Ehrlich, 1968a; Malthus, 1798)
Design criteria	A. Design for disassembly (Dario Cottafava and Ritzen, 2021) B. Precedence matrix (Mandolini et al., 2018) C. Functions of product (G. Johansson, 2008)
Embodied impacts	A. LCA (Guinée et al., 2011) B. EIO (CMU, 2018) C. Other database (G. P. Hammond et al., 2008)
System Dynamics	A. Sustainable development (Brundtland et al., 1987) B. Feedback loops (D. H. Meadows, D. Meadows, et al., 2018)
Percentage over PB	A. Assimilative/regenerative capacity of the environment (Pearce et al., 1990)

9.2 Concluding remarks

For a variety of reasons, the main problem, once equilibrium is achieved, will be distribution, not production. It is unthinkable to continue to ignore the issue of relative wealth, appealing to the growth, nor we will be able to

postpone it longer, noting that each individual should be satisfied to contrast that their share grows, absolutely, without worrying about the neighbor ...
The state of equilibrium will reduce the required contribution to the environment, but it will appeal to a much greater extent than it does today to man's moral resources

Herman Daly
as cited in D. H. Meadows, D. Meadows, et al. (2018, p.171)

A long path expects us to become fully *circular* and to enter and rest in the safe and just space. The virtuous feedback loops of innovation, technological improvement, and people behavioural change have already started. In my opinion, as already occurred in the past, technological improvement (perhaps boosted by the environmental crisis urgency) and other positive induced feedback loops will balance the excess of *externalities* we, as humanity, produced in the last centuries. Indeed, as discussed by McAfee (2019) we are already on the right path; since a few decades, we have started to produce *"more from less"*. Technological solutions already exist and, especially in the Western countries, they are starting to decouple production and economic growth from the environmental impacts and resource depletion. Although clean and green technologies have been largely adopted and are quickly spreading worldwide, the same cannot be affirmed for holistic and systemic methodologies and approaches to punctually and precisely monitor such progresses and to evaluate them in future scenarios. Can technological improvement and innovation bring humanity into the safe and just space? If they do, how fast will this transition be? Which production "configuration" will allow to last forever within this space? To answer to these, or other similar questions, in this work, and especially in this last chapter, a first broad, and still general, definition about what a circular thing is has been discussed, providing some preliminary insights on how to develop an Information System artifact able to assess a Circular Thing. On top of this, a new way of thinking, a *circular thinking*, and basic definitions are nowadays necessary.

9.2.1 Circular thinking

Circular thinking, term (i.e. circularity thinking) already introduced by Blomsma et al. (2018) in their book chapter "Circularity thinking: systems thinking for circular product and business model (re) design: identifying waste flows and redirecting them for value creation and capture", refers to adopt a systemic approach to the waste prevention and production. Their approach aims at identifying *where and why waste is being generated*, the relationships among all the parts of the system/supply chain under analysis in order to point out possible circular strategies and novel business model. This means that circularity cannot be assessed without a systemic and holistic overview of the whole process considered. In other word, as described by the Ellen MacArthur foundation, basically it means thinking in system, design out of waste and produce from renewable energy. How to translate such simple principles into precise definitions? As we have seen materials must be fully recovered, in the limit of the 100% total recovering, while energy should not exceed the total solar energy flux from the sun. The former limit will be taken into account in next decades/centuries, since no real lack of materials should occurs in the near future. The second limit, instead, as discussed in chapter 2 is still very far if compared with human energy needs and consumption. Thus, the real urgent limit, as seen in chapter 6, is related to the environmental impacts generated by each transformation process. Thus, we have seen that, a circular assessment needs to focus on the impact categories related to the planetary boundaries, by linking them to the recovering potential through design for disassembly criteria. On top of this discussion, to go further, some researches in the past decades, attempted to evaluate the energy needs to offset these externalities (e.g. carbon dioxide emissions). Indeed, relying on technological improvement, in the future even the externalities can be offset by specific technologies. For instance, Bardi (2010) evaluated the energy necessary to extract some common commercially available minerals and metals from seawater. He demonstrated that Na, Mg, Ca, and K can be extracted in a sufficient amount to fulfil human needs (indeed, there already exist commercial applications for these minerals), while Lithium, perhaps, could be extracted in the near future. For all the other minerals, instead, at the current state of technology such extraction will be unfeasible due to the high energy requirement (beyond current yearly global energy production) as consequence of the low mineral concentration in seawater. Similarly, a more recent study (Loganathan et al., 2017) analysed the most recent technological improvements for seawater mining. Typical approaches are solar evaporation, electrodialysis, membrane distillation crystallisation, or adsorption/desorption. Although the authors consider feasible in the future to mine from seawater (not to fully replace land mining but to partially support mineral requirements), they conclude that currently only a few minerals can be extracted at a sufficient rate for human needs. Another example regards carbon extraction from the atmosphere (Eisenberger et al., 2009) which in the last decade received a lot of attention from the academic community. Basically, there are two main carbon-negative technology approaches: 1) centralized air extraction (Lackner, 2003) or geoengineering solutions such as ocean fertilization or forest sequestration (Buesseler et al., 2008; Kraxner et al., 2003). Recent advancements show a noteworthy reduction in cost for CO_2 extraction techniques although still large energy costs are necessary (Eisenberger et al., 2009).

For instance, Eisenberger et al. (2009) adopted an estimation of $^{2kgCO_2}/_{kWh_{el}}$ for extraction plants. In their estimation offsetting the excess of CO_2 in the atmosphere, according to the IPCC scenarios, should be feasible within the current century. Many other examples are available in the scientific literature, although the available possible solutions are still at an early stage of development.

Concluding, I define the *general circularity* as the closed path of a material, no matter of how much energy is used to restore the original state, while the *strict circularity* is the closed path of a material without use of additional external energy (*reversibility*), avoiding human labour. As previously discussed, a circular object should fulfill, among others, the following properties:

1. *a circular object exists, if and only if, it is defined within planetary scale and boundaries*. In other words, the impacts of infinite loops for the required number of such object should be assessed and should lie within planetary boundaries. Life Cycle Analyses *per se* which simply evaluate the environmental impacts, even if a reduction of impacts or of the use of materials is proofed, does not classify a circular object. They refer only to its micro property and not to circularity.
2. *a circular object, and its reproduction and derivative, must last forever in a dynamic equilibrium, regarding the planetary boundaries, with the existing world state*. In other words, the generated impact rate must be in balance with the regeneration rate of the Planet. A strict equilibrium refers to a year by year balance between production and regeneration, while a general dynamic equilibrium may be satisfied in decades or hundreds of years, depending on the consequences.
3. a circular object is composed only by circular sub-components, materials and joints (*heritage property*).
4. two circular objects maintain the circularity if and only if are connected through a circular joint (*addition requirement*).

Towards a post-naturalist school of thought. Citing Wahl (2016) and Benyus (1997) we need to change our living approach to *learn* from Nature, instead of *extract* from her, in order to achieve win-win-win (individual, societal, and environmental) results. This deep shift cannot be done only through technological improvements. It has to be deeper, our entire place on Earth has to be questioned, as well as our approach to science. If on one side, the achievements of the scientific method and the positivist approach to study natural phenomena are unquestionable and cannot be put in discussion, on the other side, the urgency of the environmental crisis cannot be entirely faced only through a perfect measurement of every process on Earth. We need a general guide for our choices, to determine what is *right* and what is not. As stated by Benyus (1997) *"after 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts"*. We need to follow her as *model*, as *measure*, and as *mentor*, leaving the post-modernist epoch.

IV Bibliography and Index

Abbreviation

ACM Association for Computing Machinery
BaU Business as Usual
BCI Building Circularity Indicator
BE Built Environment
BEP Break-Even Point
BEPAC Building Environmental Performance Assessment Criteria
BIM Building Information Modeling
BoM Bill of Materials
BREEAM Building Research Establishment Environmental Assessment Method
BY Attribution
CAD Computer-Aided Design
CASBEE Comprehensive Assessment System for Built Environment Efficiency
CBA Cost-Benefit Analysis
CBM Circular Economy Business Model
CBM Circular Business Model
CC Creative Commons
CDW Construction and Demolition Waste
CFC Chlorofluorocarbon
CI Circularity Indicators
CLSC Closed-loop supply chain
CNC Computer Numerical Control

COP Conference of the Parties
CRM Critical Raw Materials
DARPA Defense Advanced Research Project Agency
DE Domestic Extraction
DEE Demolition EE
DfAD Design for Adaptability
DfD Design for Disassembly
DfE Design for Environment
DfF Design for Flexibility
DfR Design for Reuse/Recycling
DGBC Dutch Green Building Council
DMC Domestic Material Consumption
DMI Direct Material Input
DSP Disassembly Sequence Planning
DSS Decision Support System
DU Dobson Unit
EC Embodied Carbon
EC European Commission
EE Embodied Energy
EF Ecological Footprint
EFA Ecological Footprint Analysis
EI Environmental Implications
EIOT Environmental Input-Output Table
EMAS Eco-Management and Audit Scheme
EMF Ellen MacArthur Foundation
EPD Environmental Product Declarations
EPI Environmental Performance Indicator
EPR Extended Producer Responsibility
EROI Energy Return On Investment
ESGB National Evaluation Standard for Green Building
EU European Union
EXP Export
FAO Food and Agriculture Organization
FEW food-energy-water
GDP Gross Domestic Product
GEC Global Environment Change
GFP Global Footprint Network
GHG Greenhouse Gas
GII Gender Inequality Index
HDI Human Development Index
HEP Human Exceptionalism Paradigm
ICS International Commission on Stratigraphy
IE Industrial Ecology
IEE Initial Embodied Energy

IEQ Indoor Environmental Quality
IFPRI International Food Policy Research Institute
IMP Import
IOT Input-Output Table
IPCC Intergovernmental Panel on Climate Change
IS Information System
ISDT Information System Design Theory
IT Information Technology
KM Knowledge Management
LCA Life Cycle Assessment
LCT Life Cycle Thinking
LEED The Leadership in Energy and Environmental Design
LEI Lambert Energy Index
LOD Linked Open Data
MCI Material Circularity Indicator
MFA Material Flow Analysis
MIT Massachusetts Institute of Technology
MSW Municipal Solid Waste
MVC Mass-Value-Carbon
NC Non-Commercial
ND No Derivative Works
NEP New Environmental Paradigm
NFA National Footprint Accounts
NGO Non-profit Organization
nZEB nearly Zero Energy Building
OD Open Data
OE Operational Energy
OEM Original Equipment Manufacturer
OG Open Government
OGD Open Government
PBCI Predictive Building Circularity Indicator
PIOT Physical Input-Output Table
PV Photovoltaic
REE Recurrent EE
REE Rare Earth
SA Share-Alike
SD System Dynamics
SFA Substance Flow Analysis
SIOT Symmetric Input-Output Table
SR Supply Risk
ST Stakeholder Theory
SUT Supply and Use Table
TES Total Energy Supply
TPL Triple Bottom Line

USGS United States Geological Survey
VA Value Added
VSR Vulnerability to Supply Restriction
WEF World Economic Forum
WWF World Wildlife Fund

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V

Appendix

A. Appendix

A.1 List of keywords for Wikipedia scraper

Table A.1: Full list of keywords for the Wikipedia scraper

Type	Keywords
Final seed list	circular economy, sustainability, recycling, sustainable development, industrial ecology, waste management, life-cycle assessment, Industrial symbiosis, resource efficiency, remanufactoring, reuse, waste, anaerobic digestion, biogas, eco-efficiency, bioeconomy, food waste, bioenergy, e-waste, resource recovery, rewable energy, weee, biorefinery, municipal solid waste, climate change, eco-industrial park, resource productivity, biomass, eco-innovation, material efficiency, sharing economy, zero waste, digestate, green economy, sustainable consumption, eco-design, end-of-life, environmental resource management, Extended producer responsibility, Material flow analysis, System dynamics, wastewater, cradle-to-cradle design, supply-chain management, waste minimisation, product-service system, urban metabolism, enviromental protection, Landfill mining, 3D printing, biofuel, energy recovery, low-carbon economy, resource management, sewage sludge, sustainable products, biochar, biomethane, construction waste, business cluster, Life cycle thinking, plastic, wastewater treatment, aluminium, batteries, cement, collaborative economy, corporate social responsibility, ecological civilization, land use, metal, microalgae, reverse logistics, sludge, crop residue, biomimicry, compost, concrete, green chemistry, industrial waste, landfill, rare-earth element, refurbishment, renewable resource, waste-to-energy, biobased product, biodegradable waste, by-product, environmental economics, green logistics, lignocellulose, material flow accounting, regeneration, sustainable agriculture, biodiesel, eco-industrial development, ecological footprint, ecology, extended producer responsibility, organic waste, planned oblosolescence, bio-waste, nature-base solutions, post-consumer waste, life extension, waste sorting, social metabolism, upcycling, water reuse, adaptive reuse, bioplastic, Remanufacturing, Repurposing, hazardous waste, Sustainable transport, Waste-to-energy , Weee directive
Field type	field, policy, poli, model, branch, framework, study, subset, system, approach, area, broad, philosoph, sub-field, part, subject
Tech type	analysis, method, technolog, methodolog, technique, analytical, material, energy, chemical, metric, material, matter, practice, action, process, tool, waste, sustainable, description, strateg, model, product, treatment

A.2 Midpoint impact categories for LCA assessment

Acronym	Unit of measure	PP	PLA	PET	Glass
		A_Y			
CC	kg CO_2 eq./cup	0.137	0.608	0.331	0.480
OD	g CFC-11 eq./cup	$0.314x10^{-4}$	$1.229x10^{-4}$	$12.825x10^{-4}$	$0.632x10^{-4}$
A	g SO_2 eq./cup	0.481	4.599	1.239	3.224
POC	g Ethene eq./cup	0.033	0.295	0.205	0.138
E	g PO_4 eq./cup	0.225	2.236	0.580	0.584
NREU	MJ/cup	4.521	13.432	8.450	8.043
WSI	m^3/cup	$0.057x10^{-2}$	$0.560x10^{-2}$	$0.401x10^{-2}$	$0.159x10^{-2}$
		$C_{Y,1}$ **(Energy recovery)**			
CC	kg CO_2 eq./cup	0.081	0.240	0.124	-
OD	g CFC-11 eq./cup	$-0.048x10^{-4}$	$-0.087x10^{-4}$	$-0.039x10^{-4}$	-
A	g SO_2 eq./cup	-0.197	-0.353	-0.161	-
POC	g Ethene eq./cup	-0.010	-0.018	-0.008	-
E	g PO_4 eq./cup	-0.136	-0.261	-0.116	-
NREU	MJ/cup	-0.862	-1.602	-0.739	-
WSI	m^3/cup	$-0.023x10^{-2}$	$-0.054x10^{-2}$	$-0.024x10^{-2}$	-
		$C_{Y,2}$ **(Recycling)**			
CC	kg CO_2 eq./cup	-0.061	-0.004	-0.144	-0.281
OD	g CFC-11 eq./cup	$0.018x10^{-4}$	$-0.005x10^{-4}$	$-0.031x10^{-4}$	$-0.405x10^{-4}$
A	g SO_2 eq./cup	-0.197	-0.048	-0.619	-2.501
POC	g Ethene eq./cup	-0.015	-0.002	-0.040	-0.101
E	g PO_4 eq./cup	0.008	-0.019	-0.126	-0.358
NREU	MJ/cup	-2.712	-0.065	-4.235	-4.665
WSI	m^3/cup	$-0.020x10^{-2}$	$-0.023x10^{-2}$	$-0.283x10^{-2}$	$-0.144x10^{-2}$

(a) Values per unit adopted for production and EoL phases for the reusable cups

Acronym	Unit of Measure	PP	PLA	PET	Cardboard
			A_X		
CC	kg CO_2 eq./cup	0.019	0.025	0.033	0.019
OD	g CFC-11 eq./cup	$0.468x10^{-5}$	$0.549x10^{-5}$	$16.342x10^{-5}$	$0.231x10^{-5}$
A	g SO_2 eq./cup	0.059	0.203	0.110	0.096
POC	g Ethene eq./cup	0.004	0.013	0.023	0.006
E	g PO_4 eq./cup	0.025	0.095	0.044	0.045
NREU	MJ/cup	0.673	0.566	0.860	0.353
WSI	m^3/cup	$0.064x10^{-3}$	$0.256x10^{-3}$	$0.455x10^{-3}$	$0.159x10^{-3}$
			$C_{X,1}$ **(Energy recovery)**		
CC	kg CO_2 eq./cup	0.014	0.012	0.016	0.010
OD	g CFC-11 eq./cup	$-0.084x10^{-5}$	$-0.042x10^{-5}$	$-0.050x10^{-5}$	$-0.031x10^{-5}$
A	g SO_2 eq./cup	-0.035	-0.017	-0.021	-0.013
POC	g Ethene eq./cup	-0.002	-0.001	-0.001	-0.001
E	g PO_4 eq./cup	-0.024	-0.013	-0.015	-0.010
NREU	MJ/cup	-0.151	-0.078	-0.095	-0.058
WSI	m^3/cup	$-0.039x10^{-3}$	$-0.026x10^{-3}$	$-0.031x10^{-3}$	$-0.023x10^{-3}$
			$C_{X,2}$ **(Recycling)**		
CC	kg CO_2 eq./cup	-0.011	0.000	-0.018	-
OD	g CFC-11 eq./cup	$0.032x10^{-5}$	$-0.002x10^{-5}$	$-0.040x10^{-5}$	-
A	g SO_2 eq./cup	-0.035	-0.002	-0.080	-
POC	g Ethene eq./cup	-0.003	0.000	-0.005	-
E	g PO_4 eq./cup	0.001	-0.001	-0.016	-
NREU	MJ/cup	-0.475	-0.003	-0.544	-
WSI	m^3/cup	$-0.035x10^{-3}$	$-0.011x10^{-3}$	$-0.363x10^{-3}$	-

(b) Values per unit adopted for the production and EoL phases for the single-use cups

Midpoint impact category	**Unit of Measure**	$B_{Y,1}$ **(Onsite washing)**	$B_{Y,3}$ **(Onsite handwashing)**	$B_{Y,2,washing}$ **(Offsite washing)**	**Unit of Measure**	$B_{Y,2,km}$ **(Transport)**
CC	kg CO_2 eq./cup	0.010	0.032	0.006	kg CO_2 eq./g/km	$0.019x10^{-4}$
OD	g CFC-11 eq./cup	$0.010x10^{-4}$	$0.036x10^{-4}$	$0.007x10^{-4}$	g CFC-11 eq./g/km	$0.332x10^{-9}$
A	g SO_2 eq./cup	0.042	0.151	0.027	g SO_2 eq./g/km	$0.094x10^{-4}$
POC	g Ethene eq./cup	0.003	0.007	0.001	g Ethene eq./g/km	$0.008x10^{-4}$
E	g PO_4 eq./cup	0.029	0.105	0.020	g PO_4 eq./g/km	$0.024x10^{-4}$
NREU	MJ/cup	0.165	0.637	0.110	MJ/g/km	$0.304x10^{-4}$
WSI	m^3/cup	$1.380x10^{-4}$	$3.030x10^{-4}$	$0.962x10^{-4}$	m^3/g/km	$0.340x10^{-8}$

(c) Values per unit ($B_{Y,1}$, $B_{Y,3}$ and $B_{Y,2,washing}$) and values per gram and per km ($B_{Y,2,km}$) adopted for the use phase for reusable cups

Table A.2: Midpoint impact categories for the production and EoL phase. Representation for reusable cups (Fig. A.2a) and single-use (Fig. A.2b), and for the use phase for reusable cups (Fig. A.2c) for the different analyzed scenarios.

A.3 List of Design criteria

Table A.3: List of design criteria. Source: Issa et al. (2015).

MESO LEVEL	MICRO LEVEL
Reusable Parts	Reversible Joints
Recyclable Materials in the product	Same Material Joints
Recyclable Materials in the product	Material identification labels
Total number of products which can be reused or recycled	Tools for Disassembling
Mass Fraction of Products from Recyclable Materials	Time for Disassembly
Mass Fraction of Products Designed for Disassembly, Reuse or Recycling	Intelligent Materials
Fraction for Re-assembly	Laminated or Compound Materials
Fraction for Re-manufacturing	Painted, Stained or Pigmented Surfaces
Fraction of Recyclable Material	Total number of products with environmental instructions
Re-assembled Fraction	Diversity of Materials in Production
Re-manufacturing Fraction	Number of components
Recyclabe Material Fraction	Number of Different Materials
Recycled Fraction	Existence of Disposal / Recycling Manual
Recyclable Fraction	Disassemblability Evaluation Score
Waste Disposal Fraction	Total time for disassembly
Post-consumer Recycled Material Use	Preparation Time
Number of Recoverable Materials	Movement time
Number of Recoverable Materials	Operation Time / Disassembly Time
Number of Hazardous Materials	Post-processing time
Spare Parts and Consumables	Disassembly Time of each component
Mass Fraction of Reused Components	Disassembly time of the product
Scrap Recyclability	Fraction of Parts to Remanufacture
Product Scrap	Number of modules
Materials Reusability	Active functions
Product architecture	Number of types of fastener

Table A.3 continued from previous page

MESO LEVEL	MICRO LEVEL
Replaced parts	Total number of fastener
Parts reused after cleaning	Number of parts to be disassembled
Percentage of parts reused after repairing	Number of parts not theoretically required
Recycling Performance	Number of disassembly tasks
	Tasks which don't result in direct removal of a part
	Number of different tools
	Tool manipulations
	Hand manipulations
	Assembly Design Efficiency
	Component Type

A.4 Design for Disassembly criteria

Table A.4: Types of connection

Connection type		Weight
Dry Connection	Dry, click, velcro, magnetic connection	1
Connection with added elements	Ferry, corner, screw, bolt and nut connection	0.8
Direct integral connection	Pin and nail connection	0.6
Soft chemical compound	Kit and foam connection	0.2
Hard chemical connection	Glue, pitch, weld connection, cement bond, chemical anchors, and hard chemical connection	0.1

Table A.5: Connection Accessibility

Connection Accessibility	Weight
Freely Accessible	1.0
Accessibility with additional actions that do not cause damage	0.8
Accessibility with additional actions with reparable damage	0.4
Not accessible with irreparable damage to objects	0.1

Table A.6: Crossings

Crossings	Weight
Modular zoning of objects	1.0
Crossings between one or more objects	0.4
Full integration of objects	0.1

Table A.7: Form Containment

Form Containment	Weight
Open, no inclusions	1.0
Overlaps on one side	0.8
Closed on one side	0.2
Closed on several sides	0.1

A.5 Impact assessment of COVID-19

A.5.1 Full list of NACE codes

Table A.8: NACE Rev.2. Statistical classification of economic activities

NACE	Description
A01	Crop and animal production, hunting and related service activities
A02	Forestry and logging
A03	Fishing and aquaculture
B	Mining and quarrying
C10-12	Manufacture of food products; beverages and tobacco product
C13-15	Manufacture of textiles, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31-32	Manufacture of furniture; other manufacturing
C33	Repair and installation of machinery and equipment
D	Electricity, as, steam and air conditioning supply
E36	Water collection, treatment and supply
E37-39	Sewerage, waste management, remediation activities
F	Construction
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J58	Publishing activities

Table A.8: NACE Rev.2. Statistical classification of economic activities

NACE	Description
J59-60	Motion picture, video, television programme production; programming and broadcasting activities
J61	Telecommunications
J62-63	Computer programming, consultancy, and information service activities
K64	Financial service activities, except insurance and pension funding
K65	Insurance, reinsurance and pension funding, except compulsory social security
K66	Activities auxiliary to financial services and insurance activities
L68A	Imputed rents of owner-occupied dwellings
L68B	Real estate activities excluding imputed rents
M69-70	Legal and accounting activities; activities of head offices; management consultancy activities
M71	Architectural and engineering activities; technical testing and analysis
M72	Scientific research and development
M73	Advertising and market research
M74-75	Other professional, scientific and technical activities; veterinary activities
N77	Rental and leasing activities
N78	Employment activities
N79	Travel agency, tour operator reservation service and related activities
N80-82	Security and investigation, service and landscape, office administrative and support activities
O	Public administration and defence; compulsory social security
P	Education
Q86	Human health activities
Q87-88	Residential care activities and social work activities without accommodation
R90-92	Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities
R93	Sports activities and amusement and recreation activities
S94	Activities of membership organisations
S95	Repair of computers and personal and household goods
S96	Other personal service activities
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
U	Activities of extraterritorial organisations and bodies

A.6 Sectors' inoperability

Table A.9: Sectors' Inoperability by NACE-Code and time period

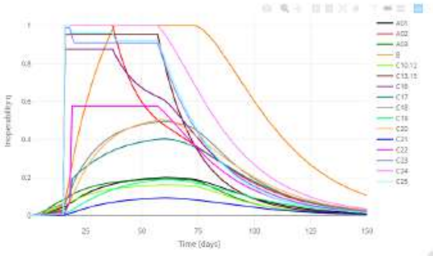
NACE										Legislative measure and effective date
	DPCM March 8th	DPCM March 9th	DPCM March 11st	DPCM March 22nd	DM March 25th	DPCM April 10th	DPCM April 26th	DPCM May 17th	DPCM May 17th	DPCM May 17th - June 11st
	March 8th	**March 9th**	**March 12nd**	**March 23rd**	**March 26th**	**April 14th**	**May 4th**	**May 18th**	**May 25th**	**May 25th**
A01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
A02	0,00	0,00	0,00	1,00	1,00	0,00	0,00	0,00	0,00	0,00
A03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
B	0,00	0,00	0,00	0,07	0,07	0,07	0,00	0,00	0,00	0,00
C10-12	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
C13-15	0,00	0,00	0,00	0,95	0,96	0,96	0,00	0,00	0,00	0,00
C16	0,00	0,00	0,00	0,88	0,88	0,00	0,00	0,00	0,00	0,00
C17	0,00	0,00	0,00	0,00	0,19	0,19	0,00	0,00	0,00	0,00
C18	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
C19	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
C20	0,00	0,00	0,00	0,00	0,10	0,10	0,00	0,00	0,00	0,00
C21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
C22	0,00	0,00	0,00	0,00	0,58	0,58	0,00	0,00	0,00	0,00
C23	0,00	0,00	0,00	0,99	0,91	0,91	0,00	0,00	0,00	0,00
C24	0,00	0,00	0,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
C25	0,00	0,00	0,00	1,00	0,96	0,92	0,00	0,00	0,00	0,00
C26	0,00	0,00	0,00	0,86	0,86	0,50	0,00	0,00	0,00	0,00
C27	0,00	0,00	0,00	0,66	0,63	0,63	0,00	0,00	0,00	0,00
C28	0,00	0,00	0,00	0,82	0,92	0,92	0,00	0,00	0,00	0,00
C29	0,00	0,00	0,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
C30	0,00	0,00	0,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
C31_32	0,00	0,00	0,00	0,80	0,80	0,80	0,00	0,00	0,00	0,00
C33	0,00	0,00	0,00	0,00	0,13	0,09	0,00	0,00	0,00	0,00
D	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
E36	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
E37-39	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
F	0,00	0,00	0,00	0,59	0,62	0,61	0,00	0,00	0,00	0,00
G45	0,00	0,00	0,42	0,42	0,42	0,42	0,00	0,00	0,00	0,00
G46	0,00	0,00	0,00	0,62	0,63	0,59	0,00	0,00	0,00	0,00
G47	0,00	0,00	0,34	0,36	0,36	0,33	0,32	0,00	0,00	0,00
H49	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H51	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H52	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H53	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
I	0,00	0,00	0,54	0,59	0,59	0,59	0,59	0,00	0,00	0,00
J58	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
J59_60	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,00
J61	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
J62_63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
K64	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
K65	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
K66	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
L68A	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table A.9: Sectors' Inoperability by NACE-Code and time period

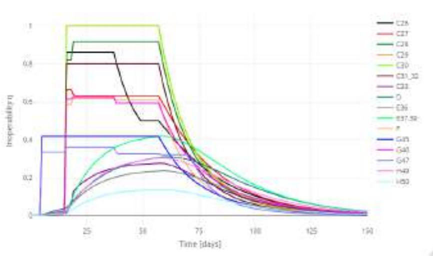
NACE	Legislative measure and effective date									
L68B	0,00	0,00	0,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
M69_70	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M71	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M72	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
M73	0,00	0,00	0,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
M74_75	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
N77	0,00	0,00	0,00	1,00	1,00	1,00	1,00	0,00	0,00	0,00
N78	0,00	0,00	0,00	1,00	0,05	0,05	0,00	0,00	0,00	0,00
N79	0,00	0,00	0,00	1,00	1,00	1,00	1,00	0,00	0,00	0,00
N80_82	0,00	0,00	0,00	0,51	0,43	0,39	0,03	0,00	0,00	0,00
O	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Q86	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Q87_88	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
R90-92	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,44	0,44	0,00
R93	0,46	1,00	1,00	1,00	1,00	1,00	1,00	0,92	0,23	0,08
S94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
S95	0,00	0,00	0,00	0,40	0,40	0,40	0,00	0,00	0,00	0,00
S96	0,00	0,29	0,57	0,57	0,57	0,57	0,57	0,29	0,29	0,00
T	0,00	0,00	0,00	0,50	0,50	0,50	0,50	0,00	0,00	0,00
U	0,00	0,00	0,00	1,00	1,00	0,00	0,00	0,00	0,00	0,00

A.7 Sectors' Inoperability

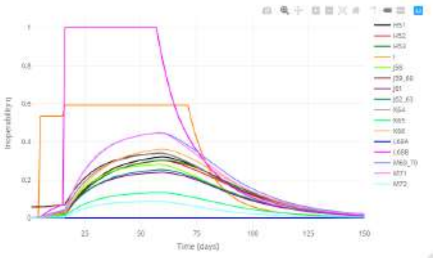
In this section, the sectors' inoperability for different values of the industry resilience matrix is reported. Figure A.1 shows the dynamic for $k = 0.1$, Figure A.2 for $k = 0.2$, while Figure A.3 refers to $k = 0.3$.



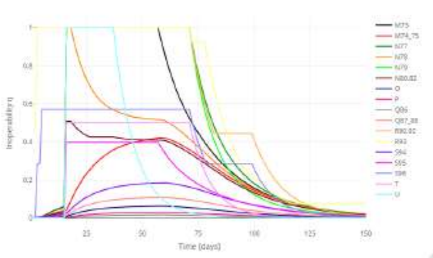
(a) Sectors 1–16



(b) Sectors 17-32

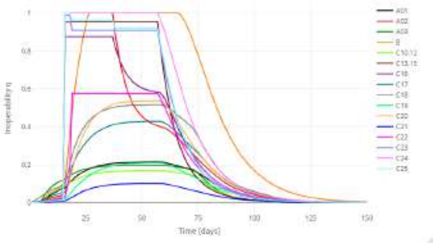


(c) Sectors 33–48

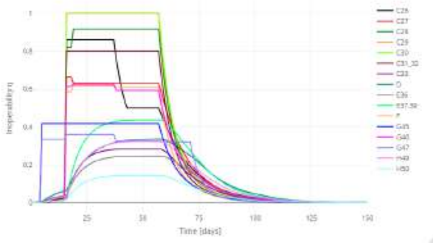


(d) Sectors 49-65

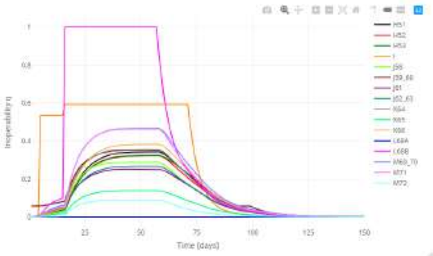
Figure A.1: Inoperability dynamic for an industry resilience value of $k = 0.1$.



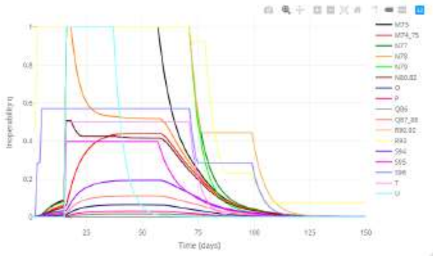
(a) Sectors 1–16



(b) Sectors 17-32

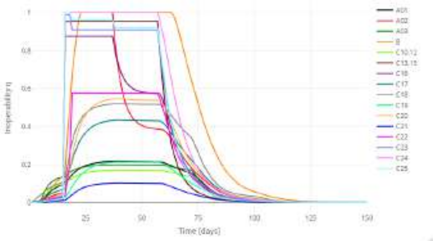


(c) Sectors 33–48

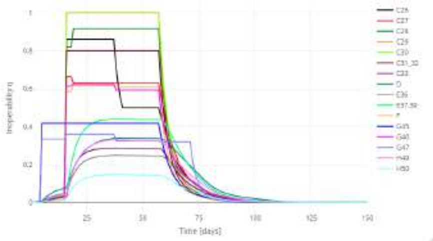


(d) Sectors 49-65

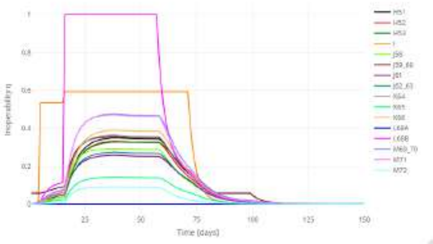
Figure A.2: Inoperability dynamic for an industry resilience value of $k = 0.2$.



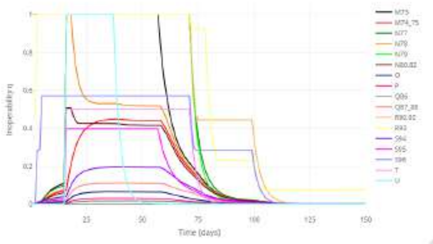
(a) Sectors 1–16



(b) Sectors 17-32



(c) Sectors 33–48



(d) Sectors 49-65

Figure A.3: Inoperability dynamic for an industry resilience value of $k = 0.3$.

A.7.1 Future scenarios

In this section, the inoperability dynamic of the Italian economic sectors for five different scenarios, during a period of 100 days, is presented. The restrictions have been supposed to run for a 30-day period. Figures, from A.4 to A.8, show the five representative scenarios for the "second wave" policies.

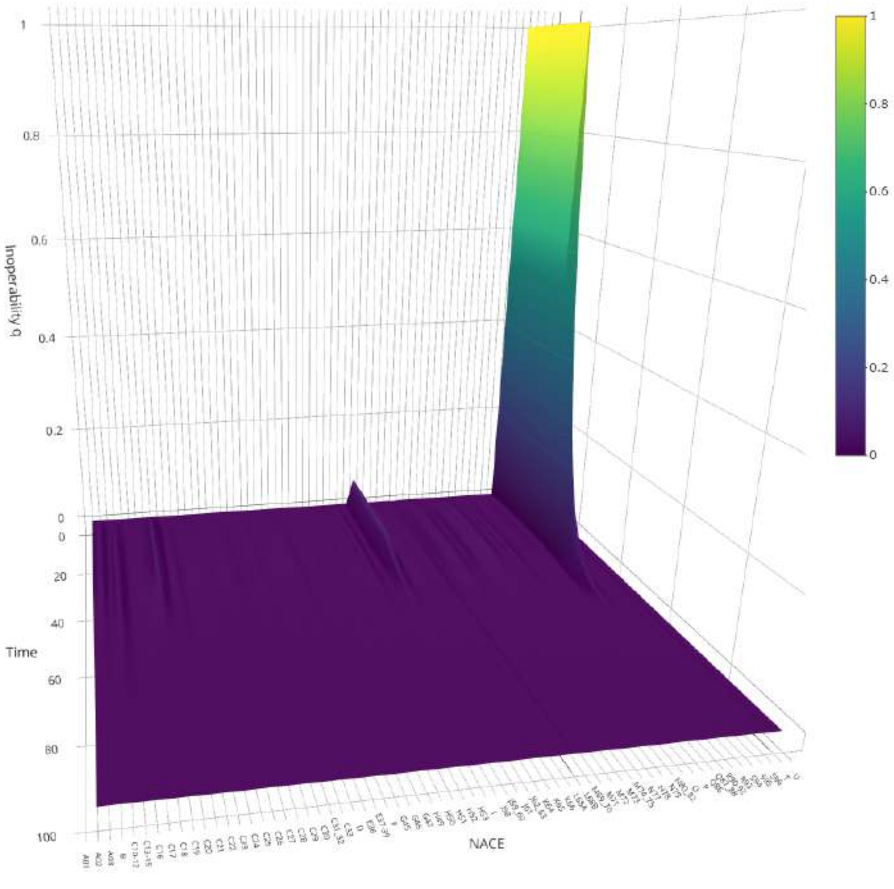


Figure A.4: Scenario 1. Restricted sectors: R93.

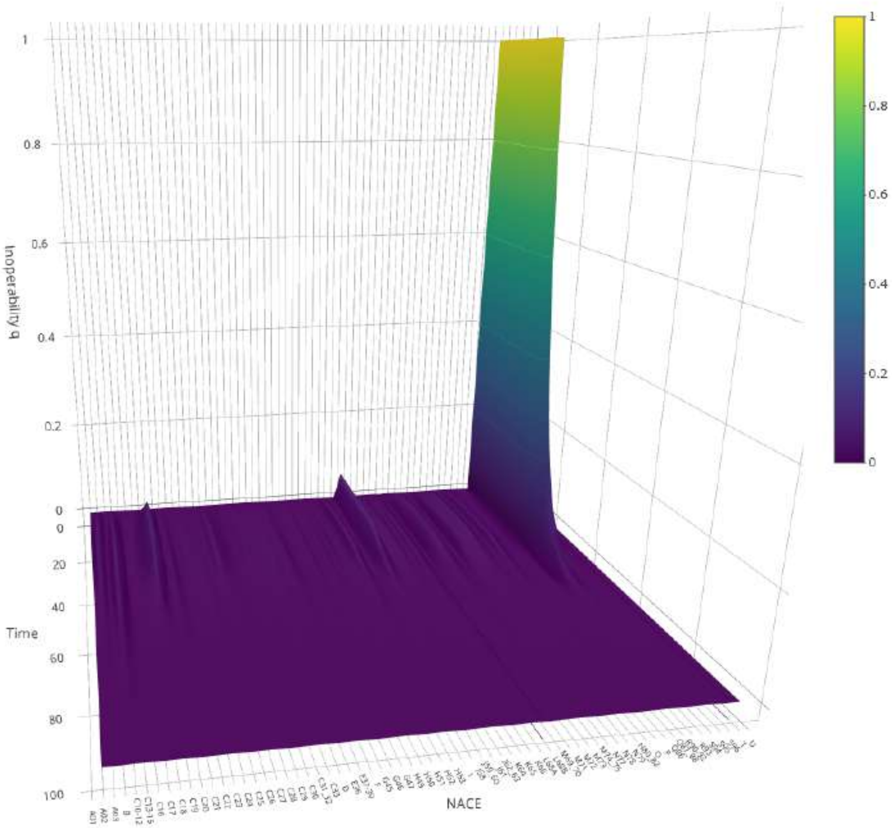


Figure A.5: Scenario 2. Restricted sectors: R93, R90-92.

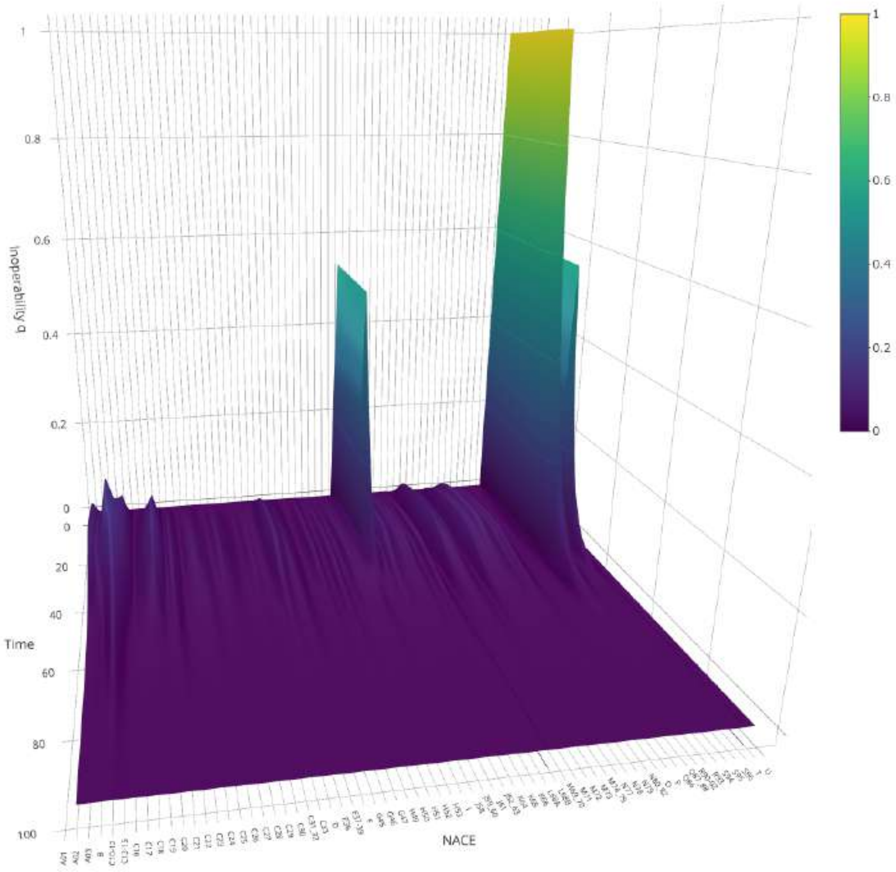


Figure A.6: Scenario 3. Restricted sectors: I, R93, R90-92, S96.

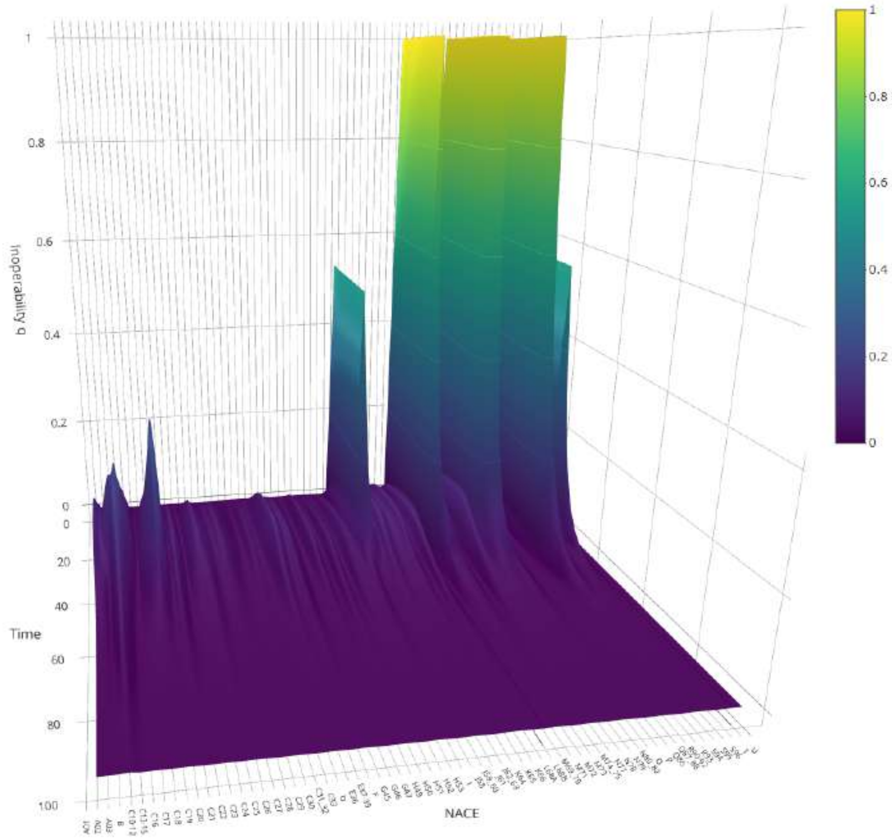


Figure A.7: Scenario 4. Restricted sectors: I, L68B, R93, R90-92, N77, N78, N79, S96

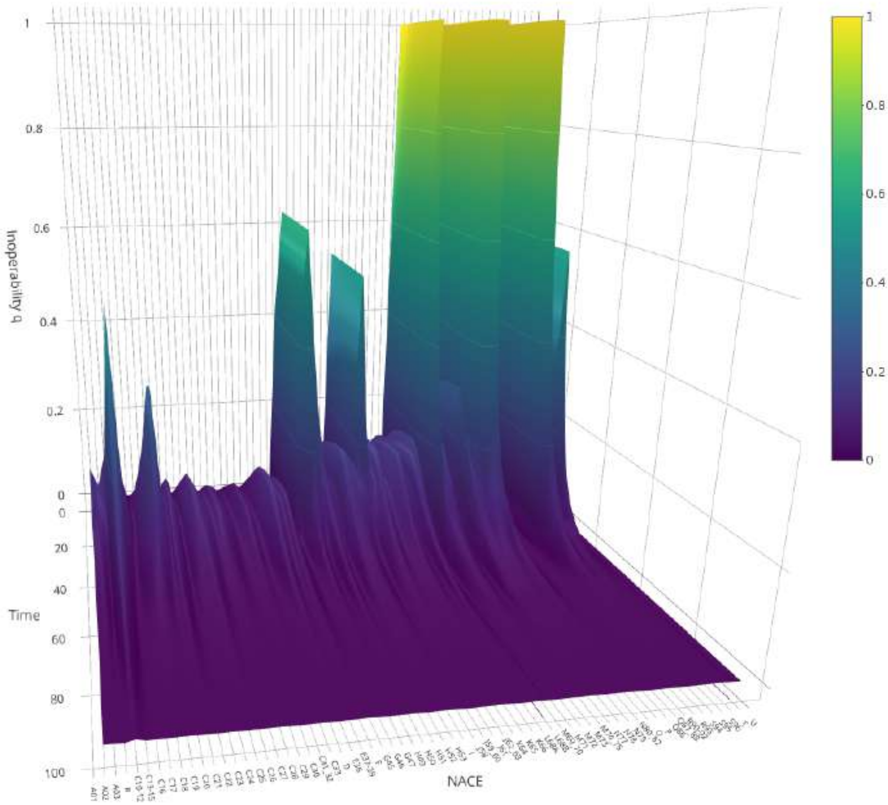


Figure A.8: Scenario 5. Restricted sectors: G45, G46, G47, I, L68A, L68B, J59_60, R93, R90-92, N77, N78, N79, S96.