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Accelerating the transition towards the Circular Economy: a new business model for resources management

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Introduction

Background

One of the basic reasons that prompted me to start the journey of an industrial doctorate such as the one in "Innovation for the Circular Economy" was curiosity. The curiosity to better understand the world, its systemic functioning and the possible development trajectories of humanity in terms of progress, prosperity and development. It is certainly not a simple challenge, but it is very stimulating for sure, also considering the job I carried out in parallel as Innovation Manager in Intesa Sanpaolo Banking Group and the strategic implications of circularity for the business world.

For the purpose of this document, I think it is right to start with one of the main questions that feed my work, as a Ph.D. student and as a professional. The question is: what will the world be like in 30 years? To hypothesize the future in 2050 and get an idea of the degree of innovation that we are allowed to imagine, we could observe how the habits of the first humans on Earth have changed compared to what we are used to today.

During the Palaeolithic period (between 200.000 and 40.000 years ago), the hominids had an average daily energy requirement of about 4.500 calories, including, for example, the calories needed for nutrition, the preparation of the first utensils and clothing, housing maintenance, travel and migration (Churchill, 2006). Today, the average American has an average daily energy requirement of about 228,000 calories (Morris, 2010), which is fifty times the requirement of a primitive man, to feed not only his stomach but also to power his car, his electric scooter, the refrigerator, the family Wi-Fi connection, his tablet and smartphone batteries – just to name a few.

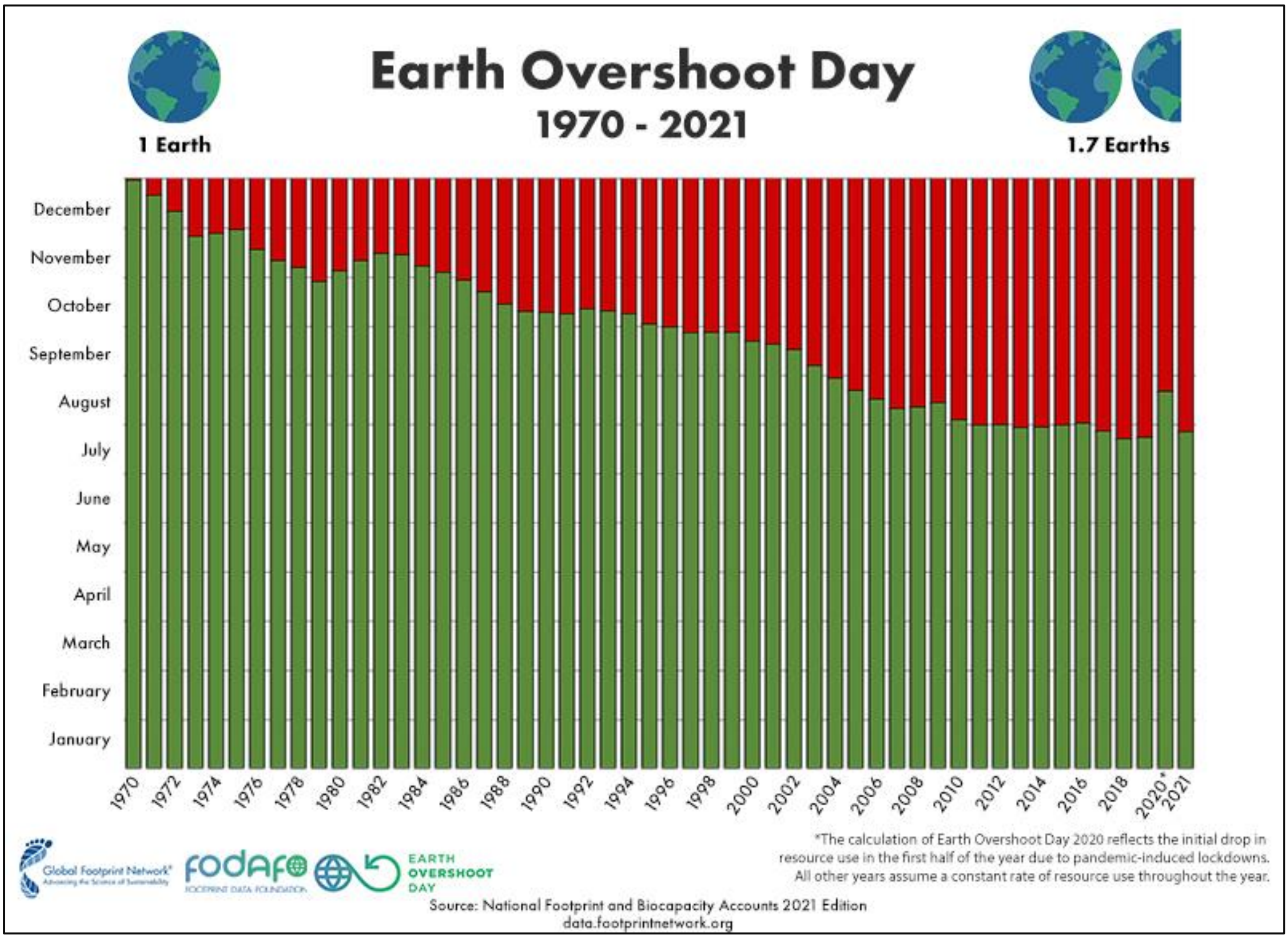
History teaches us that the more humanity prospers and advances over time, the more the need for new energy increases that can satisfy innovative technologies and evolved lifestyles (Syvitski et al., 2020; Ritchie and Roser, 2020; Dias et al., 2006). But how far can we increase the energy demand, if this connection will be still valid? How long can we prosper and grow? Is there a limit? The scientific community agrees on this: yes, the world we live in has its natural limits, and we are going far beyond that, accelerating the climate crisis through human activities (The Club of Rome, 1972; IPCC, 2021; Global Footprint Network, 2021).

As long as the production system is mainly based on the indiscriminate use of exhaustible (non-renewable) natural resources such as oil, gas, coal, fertile soil, and drinking water, then that limit will be represented by the natural capital of the Planet (UNEP, 2016; McKinsey Global Institute, 2020; Italian Natural Capital Committee, 2021; Secretariat of the Convention on Biological Diversity, 2020; Lampert, 2019), that can be defined as the global amount of natural resources and ecological services available, to sustain economic production (United Nation, 1997).

As the world's population increases, so does its consumption, and as a result we are leading many of our natural resources to their limits. When the usable oil reserves run out, we will have to be ready to produce energy from alternative and convenient sources. When the amount of fertile soil is scarce, we will have to be able to cultivate without land thanks to suitable solutions. When the reserves of precious metals are exhausted, we will have to have a plan B to produce the batteries of our mobile phones (International Resource Panel, 2019; Ritchie, 2017; Welsby et al., 2021; Panagos et al., 2015; Speirs et al., 2014)

A very interesting concept, which easily represents the effects of the current consumer model, is the Earth Overshoot Day (EOD), or the day of the earth's debt. It indicates the day of the year in which humanity comes to have taken from the Earth more ecological resources and services than the planet itself can regenerate in that year (Global Footprint Network, 2021).

As shown in Figure 1, each year the EOD gets closer and closer. In the 1970s it was between December and November, in the 1980s in October, in the 1990s in September and in the 2000s between August and late July (apart from 2020, which saw a turnaround due to the global pandemic and the consequent reduction in consumption). If we do not stop this trend of intensive consumption, in a few decades we will not have the time to start the new year that we will already be in debt to our Planet Earth.


Earth Overshoot Day
1970 - 2021

*The calculation of Earth Overshoot Day 2020 reflects the initial drop in resource use in the first half of the year due to pandemic-induced lockdowns. All other years assume a constant rate of resource use throughout the year.

Source: National Footprint and Biocapacity Accounts 2021 Edition
data.footprintnetwork.org

Figure 1 - Past Earth Overshoot Days

This happens because, unfortunately, ours is a linear production system, based on the "extract-produce-consume-dispose" concept. Raw materials are extracted from land mines, they are transformed into components and finished products. Products, after having been useful for a limited period of life, are disposed in landfills and incinerated or minimally recycled (see the Chapter 2 in this thesis to have an example for the plastic industry). In summary, the production model is not designed to give back to the Planet what we have taken. Ours is an economy that is simply unsustainable in the long term, because it is based on debt: the supply of natural resources from the Earth is unable to meet our increasing demand (International Resource Panel, 2019; Global Footprint Network, 2021).

Not to mention the effects of the modern industrial economic system linked to the massive production of waste and pollution. According to recent studies, for example, it is estimated that by 2050 we will have more plastic than fish in the oceans (Ellen MacArthur Foundation, 2016). Or, that in 2015 it was estimated that the global number of deaths due to air pollution was 8.8 million people, mainly due to pulmonary and cardiovascular diseases caused by fine particles (Lelieveld et al., 2019).

In a world that expects to host almost 10 billion people in thirty years (United Nations 2019), with a demand for natural resources more than doubled (OECD, 2018), it is therefore urgent to adopt new economic-industrial models, sustainable and capable to preserve and regenerate the natural capital of the Planet, instead of consuming it.

In recent years, among the many alternative models proposed, one stands out the most: it is the so-called Circular Economy model, an economic paradigm that systematizes the traditional concept of ecology or green with interdependent concepts such as society, equity, competitiveness and business (as explained largely in the literature review parts of the following chapters in this thesis). The circular economy is not a totally new idea. Already at the end of the 1960s, scientific researchers proposed circular industrial systems (Boulding, 1966), designed to bring flows of matter and energy back into the original sources of extraction. The theme was linked to the (environmental) sustainability of man's presence on the planet, a mandatory prerequisite to ensure a healthy and resource-rich environment for future generations as well. Only recently it has an aspect more linked to business models and the world of companies emerged, causing the attention to be raised on the issue by policymakers, institutions and investors, who see the Circular Economy as a tool to achieve most of the Sustainable Development Goals (Schroeder et al., 2018; Rodriguez-Anton et al., 2019; Schröder et al., 2020), goals of the United Nations 2030 Agenda, without losing the classic levers of profit and competitiveness of modern capitalism.

The purpose of this introduction is not to present a complete analysis of different circular economy classifications and to give a final definition (for this purpose, see Nobre and Tavares, 2021). For the purposes of the works presented in this thesis, it may be sufficient to start from the first definition given by the Ellen MacArthur Foundation:

"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts

towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." – Ellen MacArthur Foundation, 2013

Finally, the highest ambition of the circular economy, that, in my understanding collected during the PhD activity, is not to make the current industrial system more sustainable but to change towards a regenerative system, can be summarized in three fundamental pillars:

- First, eliminate the concept of waste and pollution, starting from the design phase. Design products and services that do not harm human health and the environment. Let's think about it for a moment: waste and pollution are not random, but are the logical consequence of decisions taken during the design phase; which material do I choose? How long will my product last? How do I feed the machine that will have to produce the components? What if the product needs to be repaired? etc ... Waste must therefore be seen as a design defect, something "unnatural" - in fact, in Nature the concept of waste does not exist, nothing is waste, but everything is transformed and falls within a well-defined biological cycle defined.
- Second, keep products and materials "in use". End-of-life products and materials must be reinserted into the economy and must therefore be easily disassembled, repaired and reused. To do this, of course, the role of design is again central.
- Third, regenerate natural systems. The circular economy produces value from renewable sources and encourages the use of regenerable resources such as biomaterials, thus returning valuable nutrients to the soil.

In reality, it is necessary to clarify that an economy that is only "more sustainable", based on a greater production of energy from renewable sources, will not allow humanity to reach the UN climate goals. According to the IPPC, to limit global warming to + 1.5 ° C compared to the pre-industrial era and remain below the + 2 ° C threshold, a 45% cut in carbon dioxide emissions is necessary by 2030 (compared to global CO2 emissions in 2010), to then reach zero emissions in the middle of the century (IPCC 2018). Switching to renewables could guarantee a 55% reduction in greenhouse gas emissions; however, the materials management also plays a key role in the fight against climate change and the circular economy makes it possible to cut the remaining 45% of emissions (Ellen MacArthur Foundation, 2019). Efforts to tackle the climate crisis focus on the transition to renewable sources, complemented by energy efficiency; the circular economy makes it possible to complete the picture and activate the process of remaining decarbonization of the economy (i.e. the end of the exploitation of exhaustible fossil sources).

Thesis scope and structure

The main purpose of my research, carried out through the PhD course and summarized in this thesis, has been to analyze the circular economy paradigm in general, to understand its benefits, limits, challenges and innovation key points. In doing so, I became passionate about business models related to the world of single-use plastic, in which I believe the circular economy could bring effective benefits in terms of reducing environmental impacts while strengthened the competitiveness of business models. This is why I carried out with some friends (including PhD colleagues) a pilot project in the city of Turin, described in this thesis (cfr. Chapter 2), with the goal to practically test a Deposit Return System for reusable plastic cups and apply a LCA analysis to compare different materials and identify impacts coming from reusable products compared to the single-use ones (cfr. Chapter 3) - trying to commit and evolve my research both on a theoretical and a practical field. Findings and highlights are presented in this thesis, thanks to the collection of three papers developed along my research activities.

In particular, the structure of this thesis follows the so called "three paper model" with the aim to:

- analyze the state of the art of scientific research on the circular economy through the lenses of the industrial sectors (**First Paper**); in this paper authors aim to map out past and recent studies around the concept of the CE, to identify how the industrial sectors are distributed across the CE literature. Authors start providing a comprehensive view of the CE theoretical background. Then the research continues with: i) a literature analysis on the identification and definition of economic sectors and ii) a bibliometric research on CE through the *Nomenclature statistique des Activités économiques dans la Communauté Européenne* framework (NACE) by Eurostat and European Commission, in order to answer the research question regarding which economic activities are more reviewed and which ones may still need additional scientific research around the concept of CE;
- understand the potential and examine benefits and challenges of innovative business models, with a focus for city systems (**Second Paper**); in this paper authors describe an innovative business model for an urban integrated system - aiming at transforming material flows into material stocks. The model allows private companies (food and drink providers) to reduce the usage of single-use products and the amount of exploited raw materials. A pilot project, delivered in the City of Turin and focused on the reduction of single-use plastic cups, is discussed; the business model is based on a service company which introduced a Deposit-Return System for reusable plastic cups within the urban area. The integrated system aims at reducing the splitting of the material, i.e. the plastic cups, flow by aggregating them into a new material stock. Results from one survey, related to the consumers' behavior, from a Business Model Canvas and from the Material Money Flow are presented, highlighting pros and cons;

- describe a case study which address the relationship between single use and reuse of a product (**Third Paper**); in this paper a two-step methodology is proposed to facilitate the interpretation of results during a Life Cycle Assessment (LCA). Firstly, an LCA analysis has been conducted on four single-use - Polypropylene (PP), Polylactic acid (PLA), Polyethylene terephthalate (PET), and Cardboard + Polyethylene coat - and reusable - PP, PLA, PET, and glass - cups. Secondly, the analyzed midpoint impact categories have been aggregated into three main life cycle phases: production, use and End of Life (EoL). Then, they have been used to assess the environmental break-even point (BEP), i.e. the minimum number of uses necessary for a reusable cup to be preferable than a single-use cup, considering two EoL (energy recovery, and recycling) and three use phase strategies (onsite handwashing, onsite and offsite washing). Findings highlight that reusable plastic cups reach a break-even point for climate change and non-renewable energy use for less than 150 uses, while single-use PP cups are the best option in terms of acidification, eutrophication, and water scarcity indicator. With respect to PP single-use cups, for acidification, eutrophication, and water scarcity indicator, a BEP cannot be achieved, even in the case of infinite reuses. Results evidenced all the conditions for reaching a BEP, allowing to identify possible strategies to improve the efficiency of reusable products and to obtain an environmental benefit.

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Chapter 1 – First Paper “Circular Economy: analysis of academic research distribution by economic sectors”

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Working paper (preprint).

Abstract

In the last few years Circular Economy (CE) is receiving increasing attention worldwide as the paradigm to decouple economic development from the exploitation of finite natural resources and significantly reducing environmental pressure from the economic growth of humanity. During the last couple of years, the CE concept has been more researched than ever by academics and researchers. This paper aims to map out past and recent studies around the concept of the CE, to identify how the industrial sectors are distributed across the CE literature. Authors start providing a comprehensive view of the CE theoretical background. Then the research continues with: i) a literature analysis on the identification and definition of economic sectors and ii) a bibliometric research on CE through the Nomenclature statistique des Activités économiques dans la Communauté Européenne framework (NACE) by Eurostat and European Commission in order to answer the research question regarding which economic activities are more reviewed and which ones may still need additional scientific research around the concept of CE.

Keywords

Circular economy, industry, sector, literature review, NACE, circularity

Abbreviations

- CE: Circular Economy
- EMF: Ellen MacArthur Foundation
- NACE: Nomenclature statistique des Activités économiques dans la Communauté Européenne

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1 Introduction

The Circular Economy (CE) represents an industrial and economic paradigm that is restorative or regenerative of the natural capital and aims to maximize what is already in use in all phases of the product life cycle. It is an economic model designed to regenerate itself: biological materials must be reintroduced into nature and those of technical origin must be designed to deliver the maximum possible value before disposal (Merli et al., 2018).

The current need for a shift towards that kind of model comes from the unsustainability of the open/linear "take-make-waste" economic model, in which the raw materials are extracted, transformed into finished products and become a waste after the products have been consumed (Ghisellini et al., 2016).

The CE represents a new industrial approach that aims to strongly modify the way we use our resources by replacing the open linear consumption models with closed production systems, in which the resources, thanks to the re-design of processes and cycling of materials, are reused and kept in a production cycle, allowing to generate a greater value for a longer period. This is aimed to be the way to achieve the integration of economic activity and environmental well-being in a sustainable way (Murray et al., 2017).

During the last couple of years, the CE concept has been more researched than ever by academics and researchers (Deus et al., 2017). Nevertheless, in our preliminary research, there is no evidence about how this trend impacts different business sectors and, for example, if there is a concentration of research related to specific industries.

Therefore, we aim to map out past and recent studies around the concept of the CE, in order to describe how the literature reviews are distributed across industrial sectors.

This research is based on a literature analysis and a bibliometric literature review. It analyses how industrial sectors are distributed along the scientific research related to the CE. The in-scope sectors are identified thanks to "The Statistical Classification of Economic Activities in the European Community" by Eurostat and European Commission (EC).

The central target of this paper is to identify which industrial sectors are more reviewed and which ones mainly lack knowledge and scientific research around the concept of the CE. Lastly, we suggest which sectors need to be more explored by scientific research activity and why.

This paper is structured as follows. Section 2 shows the CE origins background, its concept and principles. Section 3 describes the research design approach, presenting research questions (RQ) and methods applied, which include the industries framework above mentioned. Section 4 presents the results of the research, followed by a discussion on our findings. The paper concludes with final remarks on the contributions of this research, its limitations, and interesting fields for future research.

2 Theoretical background

The phenomenon of industrial revolution has swept the world with an unprecedented process of growth, economic development and profound socio-cultural and political changes (Siegle, 2006; Mathews, 2011; Strasser, 2000). The First Industrial Revolution (ca. 1760 - 1840) marked the transition from an agricultural-artisan-commercial system to a modern industrial system characterized by the generalized use of machines powered by mechanical energy and using new inanimate energy sources (such as fossil fuels). Thanks to an increasingly strong component of technological innovation that has included new steel making processes, mass production, assembly lines, electrical grid systems, the large-scale manufacture of machine tools and the use of increasingly advanced machinery in steam-powered factories, the Second Industrial Revolution (ca. 1870 - 1914) gave a strong boost to the industrial system, allowing an ever-greater production of goods and at an ever-lower cost.

If on the one hand this has contributed to the creation of a vast middle class, reducing the gap between the elite and the low income class, increasing the well-being of the population; on the other hand it has led to an unstoppable development of industrial production of disposable products with the explicit purpose of being discarded after use (planned obsolesce), stimulating throwaway-mindset and causing an ever increasing quantity of polluting emissions, waste production and landfills (Lieder et al., 2016). The growth of the population that drives a strong demand for the industrial sector, combined with the false perception of infinitely available resources has led to the consolidation of the linear "take-make-waste" economic model.

However, the exponential growth in the demand for exhaustible natural resources, due to the phenomena of economic and demographic development of many emerging Countries, must deal with a progressive depletion and unavailability of many of them (Meadows et al.,2004), jeopardizing the supply capacity of the companies.

The volatility of the prices of raw materials, for example, has profoundly affected the ability of companies to obtain supplies on the markets at competitive conditions, reducing operating margins and helping to create uncertainties about prospects (EMF, 2013).

At the same time huge environmental problems such as biodiversity loss, water, air, and soil pollution, resource depletion, and excessive land use are straining the very existence of the Planet (Rockström et al., 2009; Jackson, 2009; Meadows et al., 2004; WWF, 2014), leading governments to introduce waste reduction and recycling programs into their agendas. The current system is no longer working for businesses, people or the environment. The linear economy has to change with a transformation of all the elements of the take-make-waste system: how we manage resources, how we make and use products, and what we do with the materials afterwards. Only then we will create a thriving economy that can benefit everyone within the limits of our Planet (EMF et al., 2015). That is definitely one of the CE goals.

The origins of the CE thinking date back to the late 1960. Preston (2012) claims that the notion of a CE has its roots in industrial ecology, but in the work of Boulding (1966) we can already find most of the principles and concepts connected to Circular Economy. Since then, the idea has gradually evolved through the work of academics, thought leaders and business. The different schools of thought, such as the "Performance Economy" by Stahel (2006), the "Cradle to Cradle" by Braungart and McDonough (2007); the Planetary Boundaries by Rockstrom (2018) and the "Blue Economy" by Pauli (2010), have contributed to the development of the concept, paving the way of a multitude of in-depth analysis and generating a variety of definitions.

Since the mid 90' many definitions of CE started to be used to define different concepts connected to, among others, sustainable development, waste management and pollution reduction. In a comprehensive research, Kirchherr et al. (2017) collected 114 CE definitions, coming to their own one: "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.".

In a more business-oriented perspective, the CE can be considered, in contrast to the extractive and wasteful linear model, as a new paradigm that supports a different development model, resilient and regenerative by design, able to create value, thus presenting a multi trillion-dollar economic opportunity (EMF, 2015; McKinsey, 2015; Accenture 2015 and 2020; EC, 2018). The CE provides a new economic vision that considers thrive and inclusion more important than growth (Raworth, 2017) and redefines growth as decoupled from the consumption of finite resources, with benefits on business, society, and the environment. It is vital to address climate change, tackle plastic pollution, and achieve the Sustainable Development Goals (EMF, 2019).

To better define the perimeter and the objectives of a circular economy, three main principles have been stated from the Ellen MacArthur Foundation (EMF, 2019):

- Design out waste and pollution
- Keep materials in use as long as possible
- Regenerate natural capital

Waste and pollution are not accidents and can no longer be considered as simple externalities of business as usual. They are the consequences of decisions made in the design stage and, more broadly, of the misleading idea of an infinite growth on the shoulders of a finite Planet. By changing people's mindset to view waste as a design flaw and harnessing new materials and technologies, it becomes clear that waste and pollution are not created in the first place. This means that a complete change in the way objects are designed, produced, packaged and sold could completely change the amount of waste produced, during all the phases of the products use and life.

Products and materials must be kept in the economy, as a stock that can be considered reusable, up-cyclable and recyclable again and again. They should be designed so that they can be reused, repaired and remanufactured. An example can be represented by products that are sold as a service, like a circular lighting service that provides guaranteed lighting performance with regard to energy, light level and uptime. The manufacturer retains ownership of the lights and takes care of the reuse, refurbishing or recycling to ensure customers get maximum value from the lighting system (Philips Circular Lighting Service, 2017).

In nature there is no waste, everything is food and resources for something else. Being less harmful isn't enough, we should aim to be good. By returning valuable nutrients to the soil and other ecosystems, we can enhance natural resources. An example can be represented by a collection scheme and an anaerobic digestion plant that produces biogas and converts hazardous raw manure to benign and regenerating bio-solids.

The concept of circularity has emerged as a political vision around the world in recent years. It is a policy priority in China (Yuan, Bi, Moriguichi, 2006) and in Europe with the EC having adopted its Circular Economy Package in 2015 (EC, 2015) and national governments, such as the Dutch (Government of the Netherlands, 2016), the Welsh (Welsh Government, 2013) and the Scottish (The Scottish Government, 2016), also embracing the CE with dedicated initiatives (Kirchherr, 2019).

The EC launched the Green Deal in March 2020 and approved the Circular Economy Action Plan in February 2021. Key aspects of the EU Circular Economy Action Plan are connected to improving product durability, reusability, upgradability and reparability, increasing recycled content in products, while ensuring their performance and safety; incentivizing product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle (EC, 2020).

3 Methodology

The Circular Economy concepts are being adopted by a growing number of academics, policymakers and companies, but the relationship between the notions in the different industries has not been studied extensively, and the similarities and differences between them remain underexplored. To investigate the research gap, the following research questions were formulated:

- RQ 1: how economic activities are distributed along the CE scientific research?
- RQ 2: which economic activities are more reviewed and which ones may still need additional scientific research around the concept of CE and why?

To work towards answering these two research questions we conducted both a literature analysis on the identification and definition of economic sectors (3.1 paragraph) and a bibliometric research on Circular Economy by NACE categories (3.2 paragraph).

3.1 Literature analysis

Based on our research we found that the first time the literature tried to clarify the characteristics and definitions of the major economic sectors was with the study "The conditions of economic progress" by Colin Clark in 1940, with the consideration that the economy may be divided into groups of industries, since each sector exhibits significantly different characteristics (Wolfe, 1955).

Today there are several definitions of industry according to the purposes of the analysis and the subject who needs a description. For example, companies identify specific classifications to establish their strategies; statistical institutes (e.g. International Statistical Institute - ISI) use their own definitions to collect, analyse and provide data; researchers do the same to analyse performance and relationship among goods and services (Pasini, 2006).

In general terms, one of the definitions that encounter greater recognition in the literature is based on the technological similarity criteria by P.W.S. Andrews (Andrews, 1949). The author defines industry as "companies that use similar technologies and have common knowledge and experiences to produce particular goods or services". According to this definition, similar production processes are based on the same knowledge background or on the same use of a particular raw material; depending on the exclusive or prevalent use of a specific raw material it is possible to evaluate the existence of the iron industry, the wood industry or the leather industry, etc. The problem arising from this classification is that the resulting ensembles are inhomogeneous in terms of technology level; indeed, this kind of subdivision is more suitable for technologically mature industries in which there is the same innovation degree (Pasini, 2006).

In addition to the definitions based on knowledge background and raw material criterion, it is possible to define industry also according to the existence of business networks and / or distribution systems (Geroski, 1998). All goods and services that are controlled and distributed by a specific network will be part of the same *industry*. For example, the banking industry is configured as an economic activity that revolves around a series of offer terminals (e.g. branches); another example is offered by the telecommunication industry, whose optical fiber networks convey a wide range of products and services. This is an innovative criterion used by companies engaged in dynamic markets and by the antitrust authorities that regulate the public utility sectors; but it has the limit of ignoring the market and consumer's needs. On the contrary, market and demand definitions consider consumers, their needs and the functions of products. According to this criterion, "industry" can be defined as a "production process that satisfies a specific need with replaceable and/or complementary goods and services". For example, all products that satisfy the basic need for food constitute the food industry. Naturally, it is possible to further specify the need by defining more delimited industry (Pasini, 2006).

As a result of these differences, distinctive business strategies need to be implemented for different industries (Peneder, 2009). Moreover, each sector makes different use of resources, processes and technologies and has consequently a different impact in terms, for example, of negative externalities (Ritchie et al., 2017). The 2020 Emissions Gap Report by the United Nation Environment Programme can be used to show this feature (UNEP, 2020).

This study considers the sector distribution of all GHG emissions, including nonCO2 emissions. Energy transformation dominates GHG emissions, with electricity and heat generation accounting for 24% of total GHG emissions in the last decade and other energy transformation and fugitive emissions adding another 10%. Emissions from energy use in buildings and other sectors, such as agriculture and fishing, are around 7%. The industry sector has significant emissions from energy use (11% of total GHG emissions), in addition to industrial processes (9%) from mineral products (such as cement) and other chemical reactions. The transport sector has contributed to around 14% of global GHG emissions on average over the last decade, with road transport – a sector that continues to have strong growth – primarily responsible. Shipping and aviation are relatively smaller than road transport, with emissions in international territory comprising 2.2% of total GHG emissions. Agriculture and waste are 15% of total GHG emissions, with most emissions from enteric fermentation (ruminant animals, such as cattle), nitrogen fertilizers on agricultural soils, and municipal waste. Land-use, primarily associated with agricultural activities, is around 11% of the total and has larger inter-annual variations. Emissions are growing in all sectors, though there are signs that growth is slowing for electricity and heat generation, due to a stronger growth in renewables and decline in coal.

As studied by the EMF in 2019, the transition towards renewable energy sources is not enough to face the current climate crisis. GHG emissions are not falling quickly enough to achieve climate goals and shifting to renewables can only cut them by 55%. The remaining 45% comes from how we make and use products and materials, like cement, plastics, steel, aluminium and food work: these findings should be faced and solved thanks to the CE (EMF, 2019).

The above-mentioned findings show that the CE paradigm is a very complex concept, with potential impacts throughout the economy and for the different industries.

3.2 Bibliometric research

Following the set of recommendations of the three-stage process (Tranfield et al., 2003), about how to perform a systematic literature review, we divided the bibliometric research in: planning, executing, and reporting and dissemination (included in paragraph number 4, results and discussion). As experimented in the bio, green and CE fields (Ferreira Gregorio et al., 2018), this process helps researchers to classify the publications by subject of study, to analyse trends in publications and to guide them in selecting articles.

To identify the industrial sectors to analyse, we decided to take into consideration “The Statistical Classification of Economic Activities in the European Community” framework (Eurostat et al., 2008), abbreviated as NACE, by Eurostat and the European Commission. As defined by Eurostat, NACE is a four-digit classification providing a framework to describe statistical data according to economic activity in the fields of economic statistics.

The NACE classification includes 21 macro-categories (from A to U) divided into 99 sub-categories. We decided to conduct the analysis for all the 21 macro-categories; in addition, we decided to deepen also the 23 sub-categories of “C – Manufacture” macro-category, in order to have a more detailed distribution of academic research for those industrial sectors included in this macro-category (e.g. paper, textile, chemicals).

3.2.1 Planning

Web of Science (WoS) of Thomson Reuters and Scopus of Elsevier are the two main data sources for bibliometric research. Some literature reviews in the CE field identify WoS as the most important source of data for scientific bibliometric analysis, due to its consistency and standardized records (Van Leeuwen, 2006; Hou et al., 2015; Bettencourt et al., 2011; Chen et al. 2017). On the other hand, Scopus is considered to be one of the largest databases for abstracts and citation of peer reviewed literature (Nobre et al., 2017), including scientific journals, books and conference proceedings.

For a comparison among Scopus and WoS, which includes also Google Scholar, we also considered the analysis conducted by Falagas et al. (2008) and Harzing and Alakangas (2015). For the scope of this paper, we decided to use WoS because of its concentration on the peer-reviewed scientific journal articles in English, to ensure the quality of the sample (Geissdoerfer et al., 2016)

Data was collected from the WoS database in November 2020 by searching with selected strings (query) for each NACE macro-categories and for the 24 sub-categories of "C – Manufacture" macro-category. The research has been focused on titles, abstracts and keywords, looking only at papers with "article" or "review" status with no constraints on writing language and no limitation in terms of year of publication. We conducted several attempts on WoS research engine to identify the best query syntax for the purpose of this research, looking at coherency of query results compared to topics researched. A detailed list of queries, for each NACE category, is presented in Table 1.

Table 1 – List of queries used in Web of Science to research papers on CE for each NACE category

NACE Classification	Query
A - Agriculture, forestry and fishing	(Agriculture OR Forestry OR Fishing) AND Circular Economy
B - Mining and quarrying	(Mining OR Quarrying) AND Circular Economy
C - Manufacturing	*See Table 2*
D - Electricity, gas, steam and air conditioning supply	(Electricity OR Gas OR Steam OR Air Conditioning) AND Circular Economy
E - Water supply; sewerage; waste management and remediation activities	(Water supply OR Sewerage OR Waste management OR Remediation activities) AND Circular Economy
F - Construction	Construction AND Circular Economy
G - Wholesale and retail trade; repair of motor vehicles and motorcycles	- (Wholesale OR Retail trade) AND Circular Economy - (Repair AND motor vehicles) AND Circular Economy
H - Transporting and storage	(Transporting OR Storage) AND Circular Economy
I - Accommodation and food service activities	(Accommodation OR Food service activities) AND Circular Economy
J - Information and communication	(Information OR Communication) AND Circular Economy
K - Financial and insurance activities	(Finance OR Risk) AND Circular Economy
L - Real estate activities	Real estate AND Circular Economy
M - Professional, scientific and technical activities	(Legal activities OR Tax OR Management consultancy OR Public relations OR Business consultancy OR Engineering OR Scientific Research OR Natural Sciences OR Advertising OR Media management OR Public opinion OR Design OR Photographic activities OR Veterinary) AND Circular Economy
N - Administrative and support service activities	(Renting OR Leasing OR Employment placement OR Travel agency OR Tourism OR Security activities OR Cleaning activities OR Facilities support OR Packaging activities OR Office administrative activities OR Office support) AND Circular Economy
O - Public administration and defence; compulsory social security	(Public administration OR Defence sector) AND Circular Economy
P - Education	Education AND Circular Economy

NACE Classification	Query
Q - Human health and social work activities	(Hospital OR Human Health OR Dentist) AND Circular Economy
R - Arts, entertainment and recreation	(Entertainment OR Creative arts) AND Circular Economy
S - Other services activities	(Repair computers OR Repair consumer goods) AND Circular Economy
T - Activities of households as employers; undifferentiated goods - and services - producing activities of households for own use	Households as employers AND Circular Economy
U - Activities of extraterritorial organisations and bodies	Extraterritorial organisations AND Circular Economy

As anticipated in 3.2, a detailed list of queries for the 24 sub-categories of "C – Manufacture" is presented in Table 2. The combination "Manufacturing AND Circular Economy" has not been searched, preferring to indagate each subcategory of the category C – Manufacturing. In this way, the research may have missed some studies on CE that looked at the broader C category.

Table 2 – List of queries used in Web of for "C – Manufacture" category

NACE Classification	Query
C - Manufacturing	
C10 - Manufacture of food products	(Food OR Beverage) AND Circular Economy
C11 - Manufacture of beverages	Included in C10
C12 - Manufacture of tobacco products	Tobacco AND Circular Economy
C13 - Manufacture of textiles	(Fashion OR Textile) AND Circular Economy
C14 - Manufacture of wearing apparel	Included in C13
C15 - Manufacture of leather and related products	Leather products AND circular economy
C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	(Wood OR Cork) AND Circular Economy
C17 - Manufacture of paper and paper products	- Pulp AND Circular Economy - Paper AND Circular Economy
C18 - Printing and reproduction of recorded media	(Recorded media OR Printing of newspaper) AND Circular Economy
C19 - Manufacture of coke and refined petroleum products	(Oil OR Gas) AND Circular Economy
C20 - Manufacture of chemicals and chemical products	(Manufacture of chemicals OR chemical products) AND Circular Economy
C21 - Manufacture of basic pharmaceutic products and pharmaceutical preparations	(Manufacture of basic pharmaceutical products OR Manufacture of pharmaceutical preparations) AND Circular Economy
C22 - Manufacture of rubber and plastic products	(Manufacture of rubber AND plastic products) AND Circular Economy

NACE Classification	Query
C23 - Manufacture of other non-metallic mineral products	Non-metallic AND Circular Economy
C24 - Manufacture of basic metals	Metals AND Circular Economy
C25 - Manufacture of fabricated metal products, except machinery and equipment	Included in C24
C26 - Manufacture of computer, electronic and optical products	(Manufacture of computer OR electronics OR optical products) AND Circular Economy
C27 - Manufacture of electrical equipment	(Manufacture of electrical equipment) AND Circular Economy
C28 - Manufacture of machinery and equipment n.e.c.	(Manufacture of machinery OR equipment N.E.C.) AND Circular Economy
C29 - Manufacture of motor vehicles, trailers and semi-trailers	(Manufacture of motor vehicles OR trailers OR semi-trailers) AND Circular Economy)
C30 - Manufacture of other transport equipment	Manufacture of other transport equipment AND Circular Economy
C31 - Manufacture of furniture	Manufacture of furniture AND Circular Economy
C32 - Other manufacturing	Other manufacturing AND Circular Economy
C33 - Repair and installation of machinery and equipment	(Repair of machinery OR repair of equipment) AND Circular Economy

3.2.2 Executing

The research results in more than eight thousands of papers identified, with some NACE category more represented than others (ref. Table 3).

Table 3 – Number of papers identified in WoS during the execution step

NACE CLASSIFICATION	**Number of papers identified in WoS**
A - Agriculture, forestry and fishing	363
B - Mining and quarrying	240
C – Manufacture	3216
C10 - Manufacture of food products	700
C11 - Manufacture of beverages	included in C10
C12 - Manufacture of tobacco products	1
C13 - Manufacture of textiles	159
C14 - Manufacture of wearing apparel	included in C13
C15 - Manufacture of leather and related products	13
C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	154
C17 - Manufacture of paper and paper products	81
C18 - Printing and reproduction of recorded media	0

NACE CLASSIFICATION	Number of papers identified in WoS
C19 - Manufacture of coke and refined petroleum products	720
C20 - Manufacture of chemicals and chemical products	382
C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	2
C22 - Manufacture of rubber and plastic products	1
C23 - Manufacture of other non-metallic mineral products	1
C24 - Manufacture of basic metals	608
C25 - Manufacture of fabricated metal products, except machinery and equipment	included in C24
C26 - Manufacture of computer, electronic and optical products	243
C27 - Manufacture of electrical equipment	3
C28 - Manufacture of machinery and equipment n.e.c.	5
C29 - Manufacture of motor vehicles, trailers and semi-trailers	0
C30 - Manufacture of other transport equipment	0
C31 - Manufacture of furniture	7
C32 - Other manufacturing	123
C33 - Repair and installation of machinery and equipment	13
D - Electricity, gas, steam and air conditioning supply	779
E - Water supply; sewerage; waste management and remediation activities	111
F – Construction	451
G - Wholesale and retail trade; repair of motor vehicles and motorcycles	7
H - Transporting and storage	345
I - Accommodation and food service activities	11
J - Information and communication	544
K - Financial and insurance activities	16
L - Real estate activities	8
M - Professional, scientific and technical activities	1738
N - Administrative and support service activities	165
O - Public administration and defence; compulsory social security	18
P – Education	141
Q - Human health and social work activities	134
R - Arts, entertainment and recreation	3
S - Other services activities	9
T - Activities of households as employers; undifferentiated goods - and services - producing activities of households for own use	0
U - Activities of extraterritorial organisations and bodies	0
TOTAL	8299

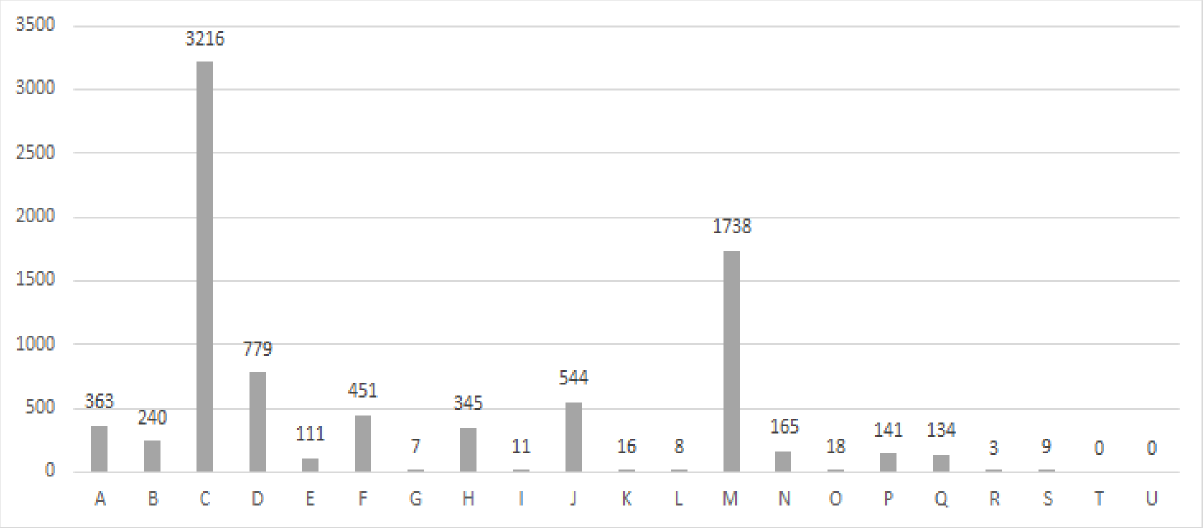
4 Results & discussion

We have analysed the results taking into consideration two research questions:

- RQ 1: how economic activities are distributed along the CE scientific research?
- RQ 2: which economic activities are more reviewed and which ones may still need additional scientific research around the concept of CE and why?

Through the selection done in WoS, using a detailed list of queries for each NACE category, we obtained a total of 8,299 papers (Tab.3 and Graph 1).

Number of papers per NACE category (Graph 1)

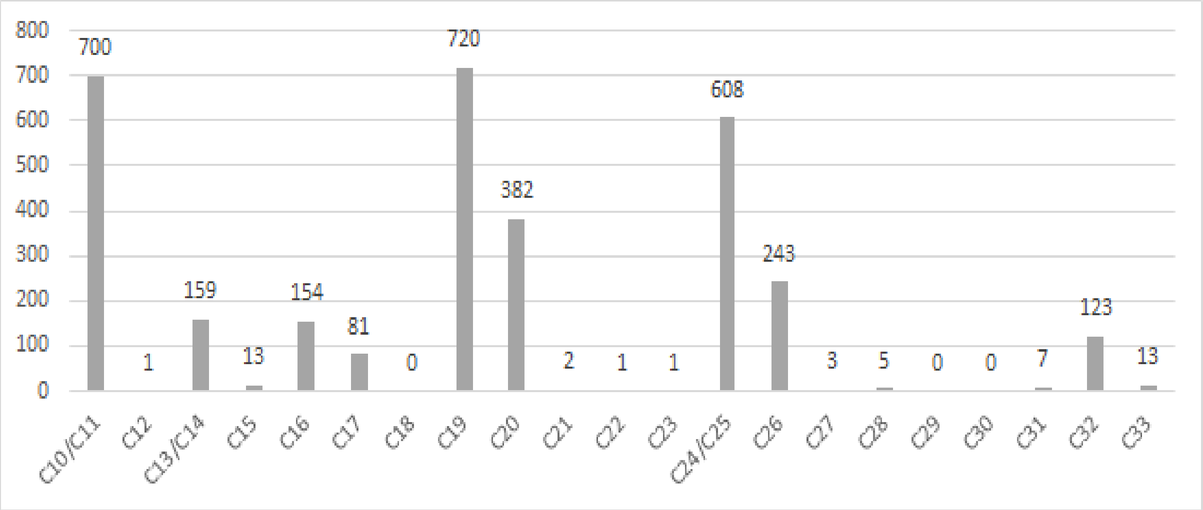


The first evidence that we found is that the most represented category is C-Manufacture, with 3,216 papers, around 38.7% of all the papers selected (Graph 1, Graph 3). The second one is M-Professional, scientific and technical activities, with 1,738 papers, around 20.9% of the total, while the third one, widely detached from the second, has been D-Electricity, gas, steam and air conditioning supply with 779 papers, 9.4% of the total amount. For some of the categories investigated and in particular T - Activities of households as employers; undifferentiated goods - and services - producing activities of households for own use and U - Activities of extraterritorial organizations and bodies, no papers were found and therefore we can consider, in this perimeter of research, that they have not been analysed by the researchers so far (Graph 1).

The category of Manufacture, that resulted as the most analysed one, represents, both from a theoretical and a managerial point of view, a very interesting area of research and we decided to go more in depth, investigating also the 24 sub-categories separately (Graph 2).

We obtained some interesting results that could be represented under three classes. A first class includes the sub-categories that exceeds the 600 papers each; then there is a second class with those sub-categories whose papers are between 80 and 400, and a third group of sub-categories whose papers are between 0 and 15.

Number of papers per sub-categories of Manufacture (Graph 2)



The first class includes only three sectors: Manufacture of coke and refined petroleum products (720), Manufacture of food products (700) and Manufacture of basic metals (608). The Coke and oil sector is one of the most impactful considering air, soil and water pollution both upstream and downstream (Working Group III IPCC, 2014). We may assume that a lot of papers relate to that issue and that CE could help innovating the different phases of the value chain - extraction, transport, logistic, refinery and distribution - with the aim to improve the life cycle impacts.

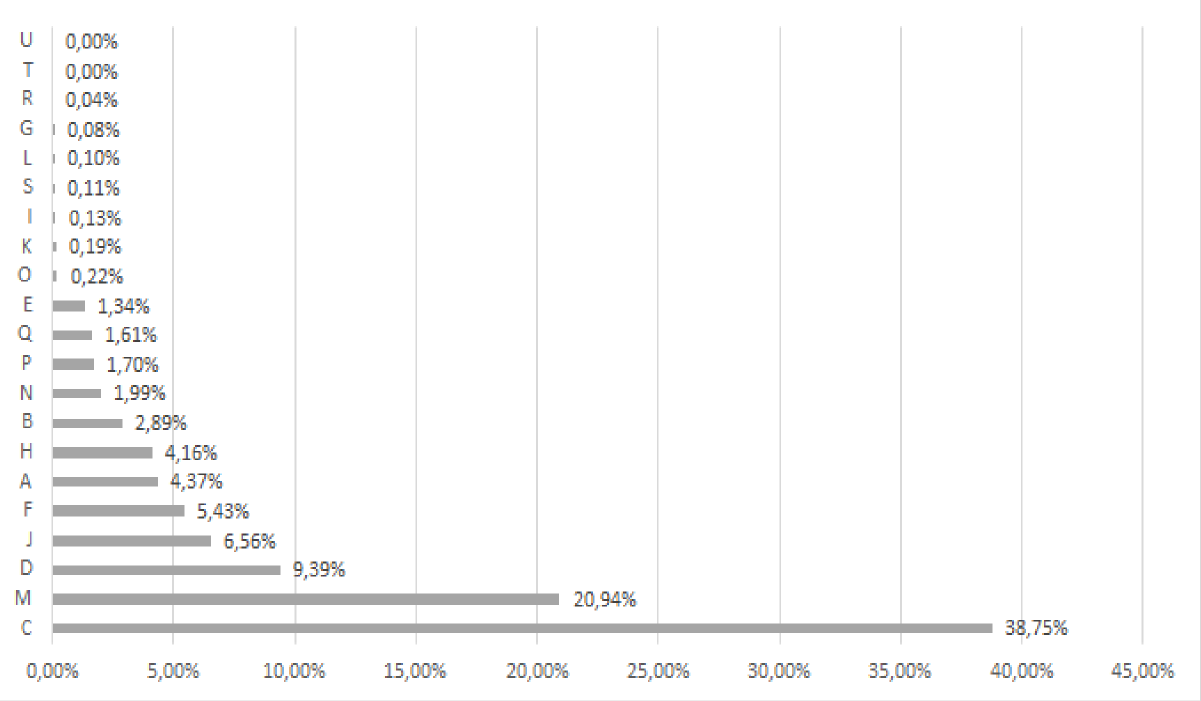
Regarding the manufacture of food products, the opportunities connected to CE innovations are well known and already put in practice by many companies. As a big amount of waste is generated during all the different phases of production, harvesting, processing, packaging and logistics, a lot of innovative activities could be developed to improve and transform this strategic sector. Also, in the sector of basic metals there are many opportunities connected to CE both considering the impact of the extraction and production phases and the availability of recycling processes and technologies.

The second class of sub-categories includes 6 sectors. The most represented one (382 papers) is C20 - Manufacture of chemicals and chemical products, then we found C26 - Manufacture of computer, electronic and optical products (243 papers) and Manufacture of textiles (159). About C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials we found 154 papers and about C32 - Other manufacturing 123. The last represented in this class is C17 - Manufacture of paper and paper products with 81 papers.

The third class includes those 15 sub-categories with very few or none papers found. Some of them have been included in some other sub-categories, for example Wearing apparel in manufacture of textiles. It seems to be worth noting that two sectors like manufacture of leather products and manufacture of furniture, virtually quite interesting from the point of view of circular redesign and new materials, count only 13 and 7 papers respectively, and that Repair and installation of machinery and equipment, that could be very interesting in prolonging the life of products counts only 13 papers.

Coming back to the other two most present categories, M - Professional, scientific and technical activities (1,738 papers) includes many different activities that could hardly be considered as a single sector, while D - Electricity, gas, steam and air conditioning supply (779 papers) is a mix of energy intense activities, on which CE could surely provide a positive impact.

Percentage of papers per category on total papers found (Graph 3)



We noted that the results of this research reflect the priority recently identified by the European policymakers in the field of CE. In fact, the last EU Circular Economy Action Plan (European Commission 2020), agreed among the European Commission and the European Parliament in February 2021, aims to focus on sectors that use the most resources and where the potential for circularity is high such as: electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients.

In general, scientists and researchers could further develop research around sectors currently less researched, bringing new insights, needs and opportunities to the policymakers, in order to develop transformative policies also in sectors like: real estate management, accommodation services, public administration and defence, financial and insurance activities.

The bibliometric research conducted in this paper may have some limitations. Where possible, we have refined the queries results looking at papers abstract and content, to filter out irrelevant publications and to select only papers coherent with the relative query; on the other hand, we considered the preliminary results as a good proxy to understand how economic activities are distributed along the CE scientific research to answer to the RQs.

After completing and experiencing the process behind this research, as a potential interesting field for future research we suggest continuing with a detailed and updated analysis of the bibliometric research results, in order to obtain new insights and intersectoral relationships. The CE topic is a key strategic point in the sustainable development agenda as of today, so it is likely to expect an increase in the numbers of CE research conducted in a year. Moreover, it could be interesting to match the research results with the sectors economic benefit expected by other dedicated research (SystemiQ, 2017), and with the environmental impact associated to each sector, to have a more complete vision and to support, for example, an investment decision-making process.

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Chapter 2 - Second Paper "From flow to stock. New circular business models for integrated systems: a case study on reusable plastic cups"

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Abstract

In recent years, the Circular Economy paradigm has gained its momentum among researchers, practitioners and policy-makers. The Circular Economy is underpinned by the transition towards renewable energy sources and circular business models following three simple principles: design out of waste and pollution, keep products and materials in use and regenerate natural systems. Such a framework needs new business applications to face the challenge on materials' transition (i.e. from single use to reuse). In this paper, an innovative business model for an urban integrated system is described - aiming at transforming material flows into material stocks. The model allows private companies (food and drink providers) to reduce the usage of single-use products and the amount of exploited raw materials. A pilot project, focused on the reduction of single-use plastic cups, is discussed; the business model is based on a service company which introduced a Deposit-Return System (DRS) for reusable plastic cups within the urban area of the City of Turin. The integrated system aims at reducing the splitting of the material, i.e. the plastic cups, flow by aggregating them into a new material stock. Results from one survey, related to the consumers' behavior, from a BM Canvas and from the Material Money Flow are presented, highlighting pros and cons.

Keywords: circular economy, reuse, material flow analysis, single-use plastic, business model

1. Introduction

The ubiquity of plastic in our everyday life and in any industrial process and commercial 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 (do Sul et al., 2014), birds (Tanaka et al., 2013) and humans (Wright et al., 2017), causing premature animals deads. Generally, plastics are fossil-fuel based and energy recovery is a common practice due to the high 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 material.

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 (European Commission, 2015; European Parliament, 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 (European Commission, 2019). 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 (BMs) have to be introduced in order to face the plastic emergency and to reduce environmental impacts by adopting Circular BM improving the reuse and the reduction of single-use plastic usage.

1.1. Circular Economy: the future-proof economic paradigm

In order to facilitate an effective circular economy understanding, the current industrial-economic system can be questioned first. The current economic paradigm is designed along what can be defined 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. First, climate change is a matter of fact: the raise of global temperatures will have noteworthy impacts on human activities and on natural ecosystems generating economic damages, desertification and agricultural productivity decrease, as well as threat to food security and human health (Intergovernmental Panel on Climate Change, 2019 and Lafakis et al., 2019). Moreover, in the current (linear) economic model, the exploitation of natural resources to drive economic activities leads to more than 11bn tons of waste annually worldwide and over 50% of Green House Gas emissions are related to virgin materials management activities - extraction, manufacturing, transportation and disposal (Organisation for Economic Co-operation and Development, 2018). On average, Europeans are consuming materials and resources at twice the speed the Planet can regenerate them (European Environmental Bureau, 2017); as a consequence, resources are becoming more expensive, due to their scarcity, and raw materials extraction is constantly becoming less sustainable (European Commission, 2017 and Food and Agriculture Organization of the United Nations, 2011).

In this context, businesses(-as-usual) across the world are dealing with several risks, such as raw materials price volatility, scarcity of resources and new consumer behaviors. On the contrary, a different economic paradigm, such as the Circular Economy, can mitigate such risks and create economic opportunities (KPMG et al., 2018). A shift in values and purposes is required for the sustainable transition (Bocken et al., 2018; Ehrenfeld and Hoffman, 2013; Bocken and Short, 2016). 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 (European Commission, 2018).

The "Circular Economy" can be the paradigm to tackle environmental issues while boosting the competitiveness of companies (European Commission, 2018); basically, it decouples economic growth from consumption of finite natural resources, by redefining the approach to value creation and natural capital regeneration. As stated by the Ellen MacArthur Foundation (EMF), the circular economy is a new economic paradigm based on three effective principles: i) design out waste and pollution, ii) keep products and materials in use and iii) regenerate natural systems. The new paradigm refers to an industrial framework that is restorative by intention, distinguished into biological and technical cycles (Ellen MacArthur Foundation, 2013 and European Commission, 2019). For businesses, there are multiple way to implement circular economy principles, depending on the side chosen (biological versus technical) and the inner / outer cycle in which the company's business model operates. As shown in the butterfly diagram of the EMF, the main scope is to minimize or, even better, eliminate waste in order to make useless waste-to-energy solutions (e.g. incinerators) and landfills, because every single product is designed to be reused, repaired, remanufactured or recycled.

The idea of a circular economy is not new. It directly derives from the industrial ecology (Bocken et al., 2016). In the 1990s, Robert Ayres 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*" (Ayres, 1994). More recently, McDonough and Braungart 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 (McDonough and Braungart, 2002). Moreover, Stahel (Stahel, 2010) discussed the fundamental difference between recycling and reuse, highlighting the importance of the latter one for a circular approach. Especially in the Food system, including packaging industry, the Circular Economy 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 (Ellen MacArthur Foundation, 2019).

The aim of this paper is to represents an example of a circular Business Model at local level, based on a reuse & redistribute model for cups and drinks in local bars, cafes, exhibitions and events, leveraging on a Product Service System (PSS). In the circular economy framework, Product Service System is a sustainable BM (Tukker, 2015) in which enterprises sell services instead of products and they directly own the products; thus, companies are responsible for the end-of-life of the products (Brezet, 2001; Charter and Tischner, 2001; Manzini and Vezzoli, 2002; Mont, 2004; Tukker and Tischner, 2006a et b). Such business model can improve user experience, optimise logistics and, consequently, lower production and maintenance costs, as well as help businesses to enhance customers brand loyalty and fit products to personal needs (Ellen MacArthur Foundation, 2019).

The rest of the paper is structured as follows. In Section 2, an overview on European Union normative framework relative on generic packaging, with a focus on Deposit-Return System (DRS). Afterwards, in Section 3, a new Business Model for an integrated DRS for reusable cups is introduced and Results based on a case study are discussed in terms of BM Canvas and Money Material Flow (MMF). Furthermore, results of a survey on consumers relative to single-use versus reusable plastic cups is discussed. Finally, in Section 4, brief concluding remarks with tips, suggestions and barriers relative to the plastic packaging ecosystem are underlined.

2. Background

Currently, many Governments (and various relevant Government agencies) are increasingly dealing with the problem of the high use of single-use plastic. For instance, Canada (Walker et al., 2018) and 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 as, 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 (European Parliament, 2019) moves exactly in the same direction, i.e. towards the reduction of single-use plastic components. The European Union 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 European Union, 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, recently, 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 (European Parliament, 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*".

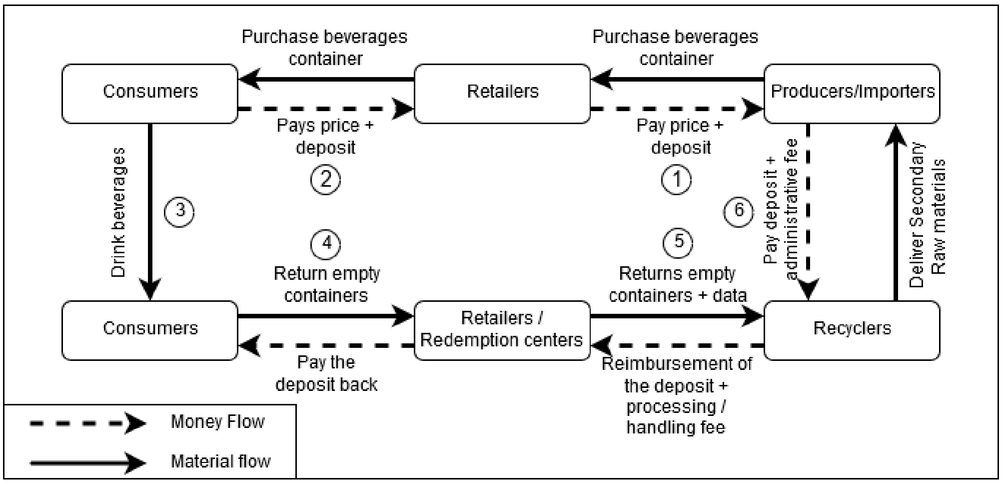
In Italy, the EU legislation has not yet been implemented. Every single region is taking steps to issue and implement legislation on its own behalf. The reference law of the Italian legislation does not aim directly at plastic waste deriving from single-use material but tends to eliminate waste at sea at the end of its life cycle, leaving fishermen "free" to collect the plastic they find in their nets, without having to throw them back into the water (Italian Government, 2019).

2.1. Deposit System background

In this subsection a brief review on common Deposit-Return Systems for beverage containers is discussed. Currently, worldwide, dozens of countries adopted a 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, 2016). Figure 1 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 such that 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 1: simplified supply chain of a Deposit System for single-use beverage containers. Adapted from CM Consulting (2016).



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. Examples of centralized national system in Europe are the cases of Croatia (Environmental Protection and Efficiency Fund), Denmark (Dansk Retursystem A/S), Estonia (Eesti Pandipakend OÜ) and Finland (Suomen Palautuspakkaus Oy - PALPA). In some cases, the central actor belongs to a few different entities such as the danish Dansk Retursystem A/S, which is a shared property of five organizations - the Dansk Retursystem Holding A/S (85.62%), the Dansk Harboes Bryggeri A/S (14.27%), the Dansk Harboes Bryggeri A/S (14.27%) and the Mineralvandsfabrikken Frem A/S (0.01%) - or, as in the finnish case, PALPA belongs to seven partners - KESKO, Alko, Puotiin, Hartwall, Sinebrychoff, Tuko Logistics, Inex Partners - where each company is specialized in a sector as drink and beverage, alcohol retail or logistics. In a few cases, there are many organizations (Rhenus Logistics, Interseroh, …) in a decentralized system, as in Germany, where the Deutsche Pfandsystem GmbH, the system administrator, is owned by the Hauptverband des Deutschen Einzelhandels (HDE) and the Bundesvereinigung der Deutschen Ernahrungindustrie (BVE), a German Retail Association and a German Food Association.

In this framework, the flow is linear up to the Recyclers and there is 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 is recycled. As shown in Figure 2, the recycling sequence consists of, at least, four steps (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 2, 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 they 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) .

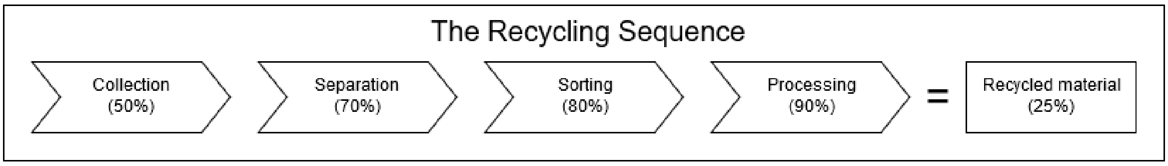


Figure 2: representation of recycling rate for a generic material reverse supply chain. Adapted from (Graedel, 2011)

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, 2016). 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). 8.43 Mt (31.1%) were then recycled, 11.27 Mt (41.6%) incinerated and 7.4 Mt (27.3%) went to landfill. 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. The percentage of recycled waste, over the total collected waste, increased from the 19% in 2006 up to the 31.1% in 2016. With respect to plastic packaging the collected waste increased from 14.9 Mt in 2006 to 16.7 Mt in 2016. In the same period, proper recycled plastic packaging increased by 74% and energy recovery by 71%. In 2016, with respect to the total of plastic packaging waste 40.9% were recycled, 38.8% went to incineration while 20.3% to landfill.

Although, it is evident the growth of percentage both of collected waste and of recycled waste, it is also straightforward that the efficiency of the collection and the recycling in EU countries can still be noteworthy improved, simply by comparing the percentage of plastic packaging properly recycled with the total return rate obtained by DRS. Table 1 resumes 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 opportunity of improvement. In fact, a DRS affects the first three stages, Collection, Separation and Sorting, as depicted in Figure 2. By multiplying the Total Return Rate with the Processing Rate as indicated in Figure 2, a first insight on the improvement margin can be obtained (Table 1).

Table 1. Estimation of Plastic Packaging Recycling Rate from a Deposit-Return System (CM Consulting, 2016) and Countries Recycling Rate (Plastics Europe, 2017)

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)

3. Results and discussion

A case study, i.e. Plastic Free Movida (PFM), within 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 MMF for single-use beverage containers described in Figure 1 it is possible to transform constant material flow into a temporary material stock. The PFM Business Model has been introduced by an italian NGO named greenTO in 2019 within 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 have not 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 retailer involved in the network. The case study is analyzed in terms of MMF and BM Canvas, highlighting the involved stakeholders. Finally, results from a survey on consumers' behavior is pointed out.

3.1. Money Material Flow

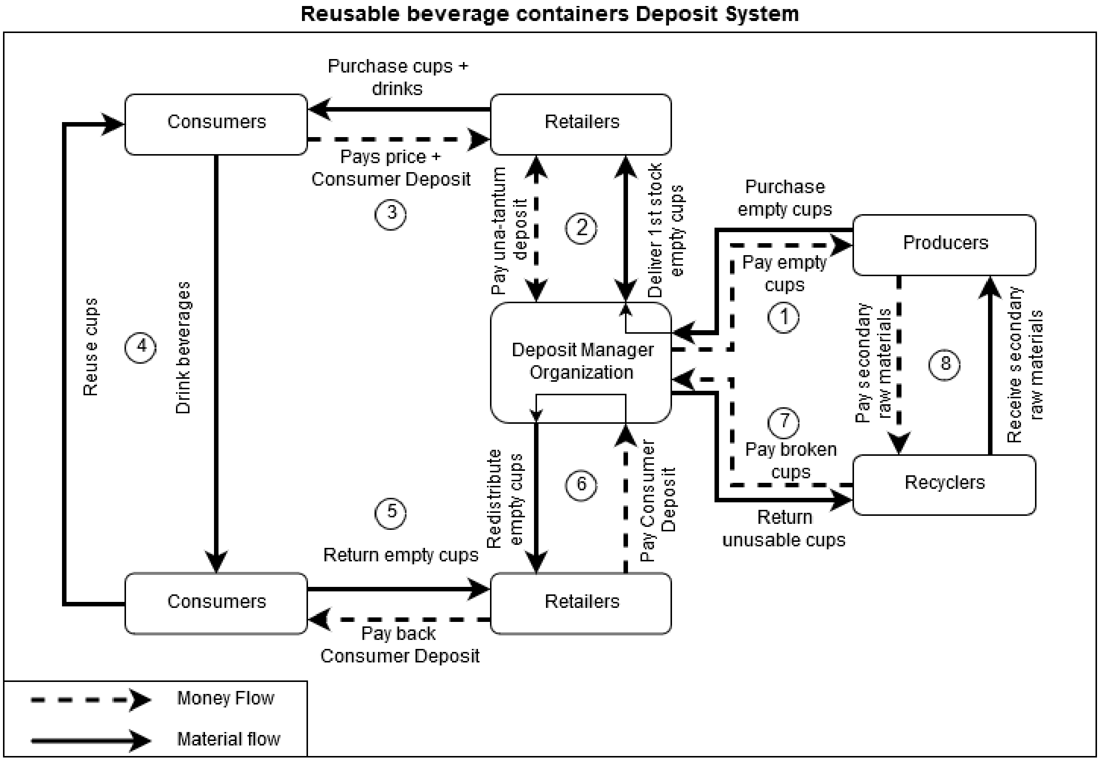


Figure 3: representation of a reusable beverage containers Deposit-Return System.

In this section, the Money Material Flow is described. The DRS here analyzed is pretty similar to the one described in Figure 1 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 man in the middle 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 agreement 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.

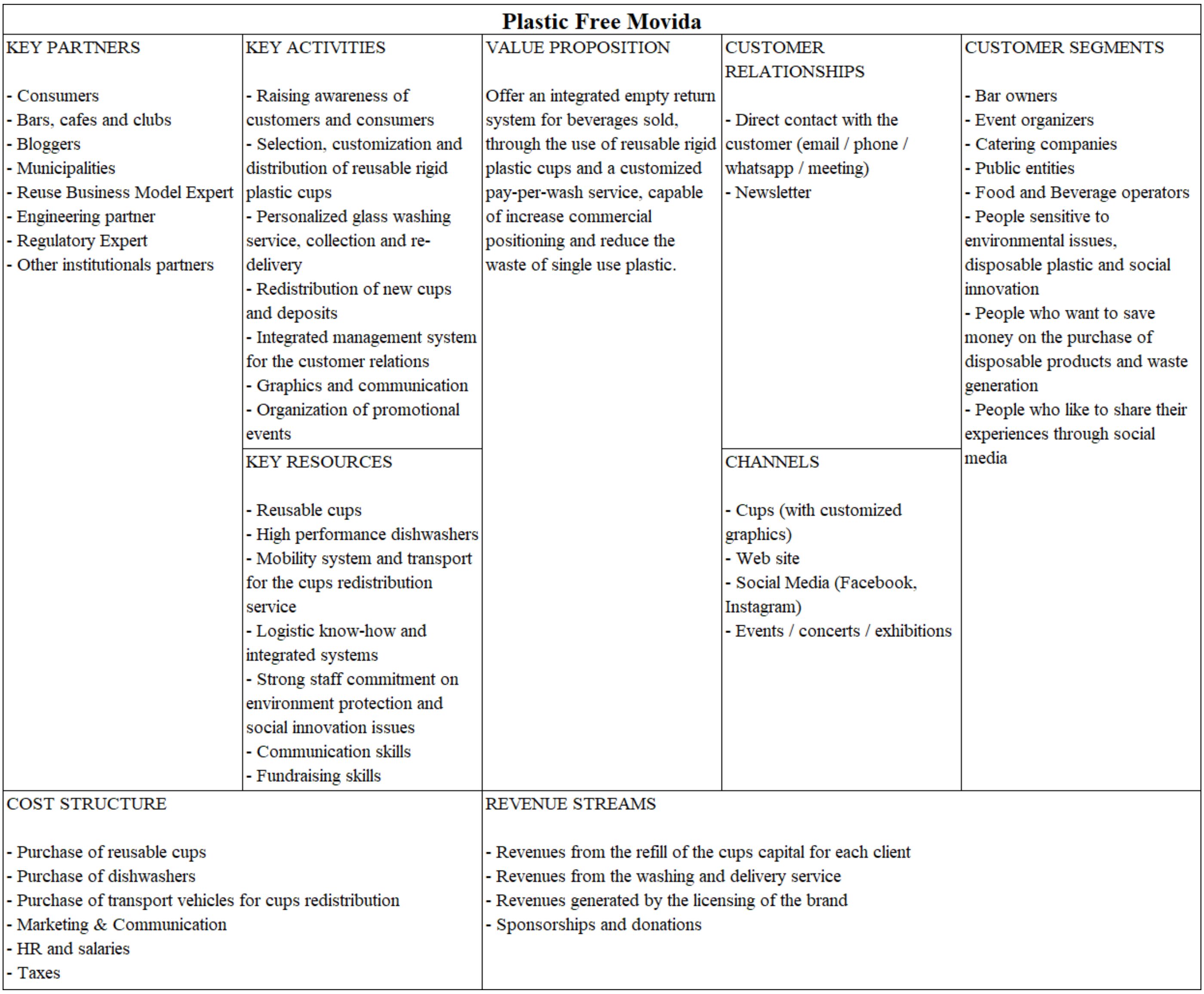
The agreement between the DMO and the Retailers can be one, or many, yearlong and it guarantees to the Retailers, for all the life of the agreement, to have a constant stock of cups. Third, as in the single-use DRS, Retailers deliver the empty cups to Consumers when they buy a beverage by receiving the Consumer Deposit (3) and consequently, Consumers use, and re-use, the cups as many times 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 to 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 meaning is to balance 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, e.g. 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, in other words, based on the same logic of the single-use containers Deposit System, increases the life of each cup from few minutes to years by stacking the flow of materials within the steps (3), (4), (5) and (6) and transforming a constant flow of materials made by single-use products into a, temporary (a few years), stock of materials.

3.2. 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. Out of what is described in Figure 4, a couple of considerations:

- in order to maximize the awareness on single use plastic consumption and its impact, 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.



<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 4: Business Model Canvas of Plastic Free Movida case study for a Deposit-Return System for reusable cups.

3.3. Analysis of customer 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 within the Turin's nightlife. Two hundred and twenty-eight answers were collected (27 in english from foreigners and 201 in italian). The survey was composed by three main sections: 1) personal and registry 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% 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 asked, as well as if consumers usually drink their beverages in plastic or glass cups. About the drinking habits there were three questions: 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 facing with reusable plastic cups and their perception with respect to the service of recycling of single-use plastic cups. There were 6 main 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 cup and a 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 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 behavior is further confirmed by the scarce trust into 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 with reusable plastic cups. Only 4% declared to feel uncomfortable to drink into a reusable cup due to hygiene, while 48% stated both to be adverse if the cups are not properly washed and to not have any 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' behavior on picking up empty cups within 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.

4. Concluding remarks

In this paper a Product Service System for a Deposit-Return System for reusable cups has been introduced. The pilot project here described, run in the city of Turin in the month of July and August 2019 and still active, allowed to transform a flow of material into a temporary stock of material. The case study has been validated by a survey related to 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 dispose 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 within a city for a targeted product (in this case, plastic cups). Even if, 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 done in order to compare classical single-use container DRS with the proposed DRS for reusable cups and to identify possible inefficiency, from an environmental point of view, and to reveal the "environmental break-even point".

Indeed, the production of reusable cups need 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 squanders a large amount of water. Second, current plastic cups producers are selling products, i.e. reusable cups, only tested, in a large scale, during temporary, from a few days up to a few weeks' large festival. Thus, the effective durability of a reusable cup is still to be assessed within the daily life of a bars. It is clear that within bars, restaurant and clubs of a city the usage is much more intensive with respect to a time-limited event. Finally, eventually 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 simpler 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 within the city, it may be possible to collect current unavailable data on several social phenomena related to the nightlife.

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Conflict of interest
The principal investigator Dario Cottafava is one of the cofounder of the promoting NGO involved in the case study described.

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Chapter 3 - Third Paper “Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups”

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Abstract
The Circular Economy introduced new research challenges to be faced. Linear and circular supply chain comparisons require general methodologies to obtain significant and scalable results. A two-step methodology is here proposed to facilitate the interpretation of results during a Life Cycle Assessment (LCA). Firstly, an LCA analysis has been conducted on four single-use - Polypropylene (PP), Polylactic acid (PLA), Polyethylene terephthalate (PET), and Cardboard + Polyethylene coat - and reusable - PP, PLA, PET, and glass - cups. Secondly, the analyzed midpoint impact categories have been aggregated into the three main life cycle phases: production, use and End of Life (EoL). Then, they have been used to assess the environmental break-even point (BEP), i.e. the minimum number of uses necessary for a reusable cup to be preferable than a single-use cup, considering two End of Life (energy recovery, and recycling) and three use phase strategies (onsite handwashing, onsite and offsite washing). Considering offsite washing - transport distance of 20km and industrial washing machines - and energy recovery, findings highlight that reusable plastic cups reach a break-even point for climate change and non-renewable energy use for $n<150$, while single-use PP cups are the best option in terms of acidification, eutrophication, and water scarcity indicator. With respect to PP single-use cups, for acidification, eutrophication, and water scarcity indicator, a BEP cannot be achieved, even in the case of infinite reuses. Results evidenced all the conditions for reaching a BEP, allowing to identify possible strategies to improve the efficiency of reusable products and to obtain an environmental benefit.

Keywords: Life Cycle Assessment, Circular Economy, Environmental break-even point, Reuse, Reusable plastic, Plastic cup

1. Introduction

Plastics are lightweight, durable and cheap materials. Since the ’60s, plastics, gradually substituting other materials such as wood, metal, and glass, have become the ubiquitous materials of the modern economy (Ellen MacArthur Foundation and World Economic Forum, 2016) due to their chemical properties and the low cost of raw materials. Plastics production is regularly growing and, nowadays, global production reached 359 Mt in 2018 and an industry turnover of 355 billion euros in 2017 in Europe (Plastics Europe, 2019). On the other hand, plastic waste causes impactful consequences in the environment (Jiang, 2018), in terms of degradation of natural systems (Ryberg et al., 2019; Jambeck et al., 2015), large quantity of greenhouse gas emissions, fossil feedstock depletion (Hopewell et al., 2009) and toxic additives circulation (Swan et al., 2015; Lien et al., 2015; Winton et al., 2020). The plastic issue have captured the attention of the public and private sectors around the world (European Commission, 2015; European Parliament, 2019; Ellen MacArthur Foundation, 2019). The industry is showing its inclination to gradually move away from today's linear take-make-dispose model (Ellen MacArthur Foundation, 2016), by adopting innovative circular business models. So, waste is designed out from the linear model and resources are circulated back to the soil (compostable plastic) (Razza et al., 2009), to the producers (recycled plastic) (Accorsi et al., 2020), or to the consumers (reusable plastic) (Changwichan and Gheewala, 2020).

Today the efforts towards the increase of recycling practices are remarkable, but still not sufficient. The plastic packaging recycling rate in European Union cannot be considered satisfactory at all, with an average percentage of 41% in EU 28+2 and a target for plastic packaging recycling of 50% by 2025 (Plastics Europe, 2018). At 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 plastics or differentiated value-added taxes for recycled plastics, the introduction of recycled content standards, targeted public procurement requirements, or recycled content labelling, just to name a few.

An increasing number of countries are taking measures to reduce single-use plastic dispersion into the natural environment and, in 2019, the European Parliament issued a Directive (2019/904/EU) aimed at directly limit the production of determined single-use plastic products (European Parliament, 2019) (cups are one of these). Despite new recycling policies, promoting reuse remains the main effective solution to reduce the accumulation of plastic waste. In fact, to ensure reusability, the first step is to encourage the deposit return system (Cottafava et al., 2019). Several European Union (EU) countries already adopted national legislations to increase the use of reusable plastic with deposit return systems (CM Consulting Inc and Reloop Platform, 2016). Although reusable products can successfully limit the use of virgin materials and can have a positive effect on the material extraction / production, the positive impact could not be always positive by considering various environmental indicators. An effective approach for an objective evaluation of these indicators is given by the use of the Life Cycle Assessment (LCA) methodology.

LCA 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 materials (Garrido and Del Castillo, 2007; Almeida et al., 2018; Tua et al., 2019; Paspaldzhiev et al., 2018). 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 condition, End of Life (EoL) scenario or functional unit. Indeed, nowadays, an open debate within the Circular Economy (CE) framework is emerging on how to model multicycle circular processes including reuse, repair, refurbish or remanufacturing (Amasawa et al., 2020).

Dealing with different kinds of electrical and electronic products, Ardente 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 influences the assessment of the environmental impact. A similar study (Boldoczki et al., 2020) came to the conclusion that reuse is not always preferable to recycling. 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 equipments, 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 (Ardente and Mathieux, 2014; Boldoczki et al., 2020), 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 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 – in case of reuse, repair, remanufacturing, refurbishing. For instance, Bobba et al. (2016) proposed a set of environmental and economic indicators to evaluate products 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 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 work a methodology for the interpretation of results is proposed, in order to facilitate comparisons between single-use and reusable products. To easily identify the BEP, the product efficiency (the efficiency of the production and EoL 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. This methodology has been applied to a case study, comparing four single-use cups with four reusable cups, by analysing seven impact categories in three different use phase scenarios and two EoL scenarios.

The following of the paper is structured as follows. In section 2, the novel methodology is described by highlighting the differences with a traditional LCA analysis. In Section 3, the comparison between reusable and single-use cups is discussed in terms of the environmental break-even point. In Section 4, main results are compared with previous findings in the literature and some limitations of the proposed methodology are pointed out. Finally, in Section 5, main results are summarized.

2. 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 no. of uses "n", the environmental BEPs for each analyzed impact category.

2.1 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 studied system 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 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 The baseline 0) case consists of using the cup once and then throwing it for disposal. The use phases have been modelled according to Martin et al. (2018) for 1) onsite handwashing, and 3) onsite washing with commercial washing machines. The onsite washing is modelled for the real situation, when 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 (European Parliament, 2020). So, two scenarios have been considered: 1) 100% energy recovery, and 2) full recycling or, in the case of PLA cups, composting.

2.2 Life Cycle Assessment

LCAis 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 (International Organization for Standardization, 2006a,b). The entire work was conducted with software SimaPro 8 and using the Ecoinvent v.3.3 database.

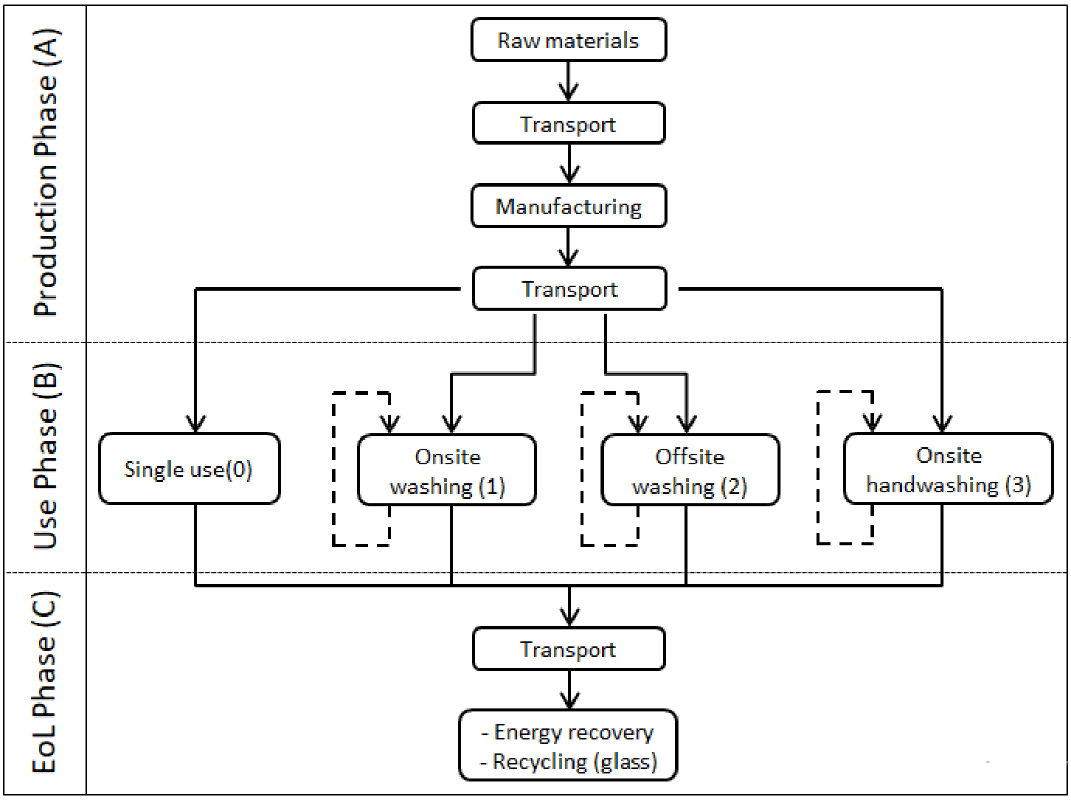


Figure 1: Overview of the analyzed scenarios.

2.2.1. 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 breakeven 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 modelling 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 1.

2.2.2. Life cycle inventory.

The weights of the cups considered in the study are summarized in Table 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.

	Reusable Weight [g]				**Single-use Weight [g]**			
	PP	PLA	PET	Glass	PP	PLA	PET	Cardboard
Min	35	150	60	330	6	6.5	8	7.5
Avg	40	175	70	360	7	7.5	9	8.5
Max	45	200	80	390	8	8.5	10	9.5

Table 1 Minimum, maximum, and average weight of the analysed single-use and reusable cups.

The sources from which all inventory values were derived or measured are indicated in Table 1 in section B of the Supplementary Information (SI). Input-output data for the production, use and the EoL phases, are specified in Tables 2, 3, 4, 5, and 6 in section B of the SI.

The production of the plastic cups was modelled using the thermoforming and injection moulding processes for single use and reusable respectively (Crawford and Martin, 2020; Changwichan and Gheewala, 2020). Given the lack of specific data related to the production of PET cups, the system was modelled 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 neighbouring states in a territory such as Europe. Both transports have been modelled assuming a road service that uses freight lorries of 16-32 tons. Instead, the transport in the use phase (Table 4 in section B of the SI), used in the offsite washing scenario, takes place with a light commercial vehicle. The use phase has been modelled 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 Martin et al. (2018); the usage data of water, detergents, and energy were reported. The data for modelling 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 modelled 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 and Mintz, 1994). PLA is not recycled, but it can be composted according to Vercalsteren et al. (2007).

2.2.3. 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 CMLIA 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.

2.2.4. 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 LCAanalyses. The introduction of the environmental BEP, the product efficiency and the use phase efficiency, as it will be described in next subsection, allows to decouple the effects of a change in the production phase (it affect only "when" the BEP is achieved) or in the use phase (it affect "if" the BEP is reached) by facilitating the comparison among reusable and single-use products.

2.3. Break-even point assessment

To evaluate the BEP, according to Figure 1, 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 the different scenarios;
4. the subscripts also highlight the product material.

With this notation, for instance, $B_{PLA,Y1}$ is the impact of the use phase for the reusable PLA cup for onsite washing. 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 now, the materials' subscripts and considering only the baseline scenario without closedloop (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:

$$X = A_X + B_X + C_X \tag{1}$$

$$Y_0 = A_Y + B_{Y0} + C_Y \tag{2}$$

The use phase impact for the baseline, i.e. the life cycle without loop, has been considered equal to zero (B_X, $B_{Y0} = 0$). According to this notation, three Key Performance Indices (KPIs) for a reusable product can be defined, as described in the following.

2.3.1 Product efficiency

The environmental product efficiency for reusable products KPI is defined as:

$$\eta_p = \frac{Y_0}{X} \tag{3}$$

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.

2.3.2. Use phase efficiency

The environmental use phase efficiency for reusable product KPI is defined as:

$$\eta_{u,j} = \frac{B_{Y_j}}{X} \tag{4}$$

where B_{Yj} 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_{Yj} 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.

2.3.3 Environmental break-even point

The environmental break-even point KPI is calculated as:

$$n_j = \frac{Y_0}{X - B_{Y_j}} \tag{5}$$

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. The proof and rationale of Eq. 6.5 is explained in section A.1 of the SI.

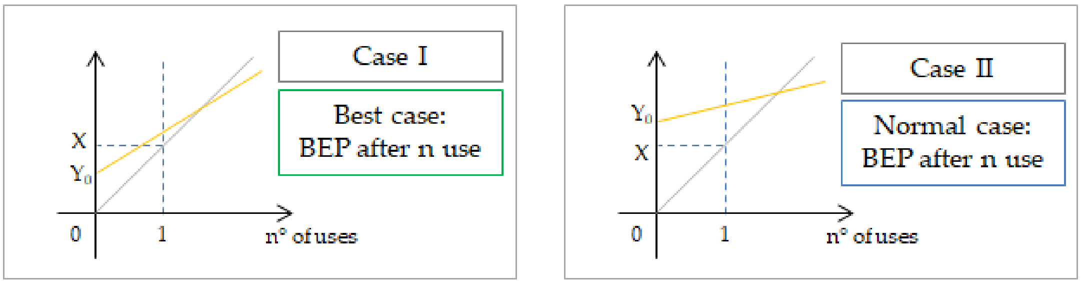
By substituting Eq. 3 and 4 into Eq. 5, the environmental BEP can be expressed in terms of the product efficiency η_p and the use efficiency $\eta_{u;j}$ according to:

$$n_j = \frac{\eta_p}{1-\eta_{u,j}} \tag{6}$$

From equation 5, two cases emerge. If $X > B_{Yj}$ implies that $n_j > 0$; 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 $X < B_{Yj}$ then $n_j < 0$; thus, the reusable product does never reach an environmental BEP, since a negative number of usages is not possible.

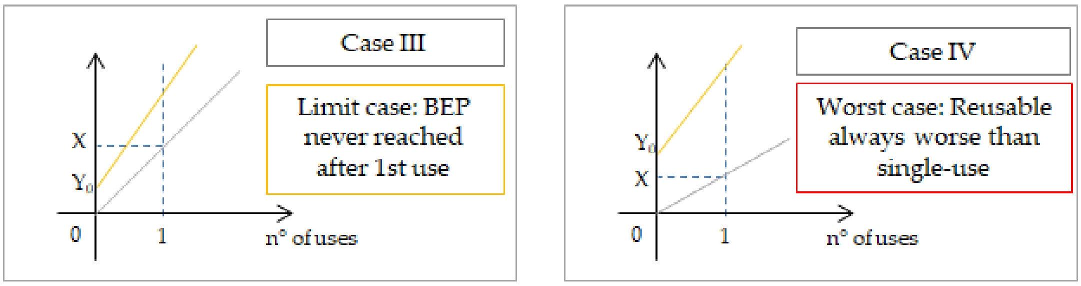
2.3.4 Mapping cases

From Eq. 3, Eq. 4 and Eq. 5 (or Eq. 6) four possible cases may be identified which explain the behaviour of the reusable with respect to the single-use product life cycle impacts. Figure 2 shows the four possible cases to compare reusable vs single-use products. The representation in Figure 2 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 is given by B_{Yj}. With this formalism, the single-use line passes from the origin while the reusable line crosses the y-axis at Y_0, and if $X = B_{Yj}$, n_j tends to infinite, as the two straight lines are parallel.



a) Efficient production and use phase.

b) Inefficient production phase and efficient use phase.



c) Efficient production phase and inefficient use phase.

d) Inefficient production and use phase.

Figure 2 Environmental break-even point representation of the four possible cases comparing reusable and single-use products. The y-axis represents the related midpoints. Gray lines refers 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.

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	$n_j < 0$	$\eta_p > 1$	$\eta_u > 1$

Table 2. Four cases and relationships with the n, ηp, and ηu

According to Table 2, 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.
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.

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 described in Table 2, 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 ($\log(\eta_u) > 0$; $\log(\eta_p) > 0$), as reported in Figure 2.1.

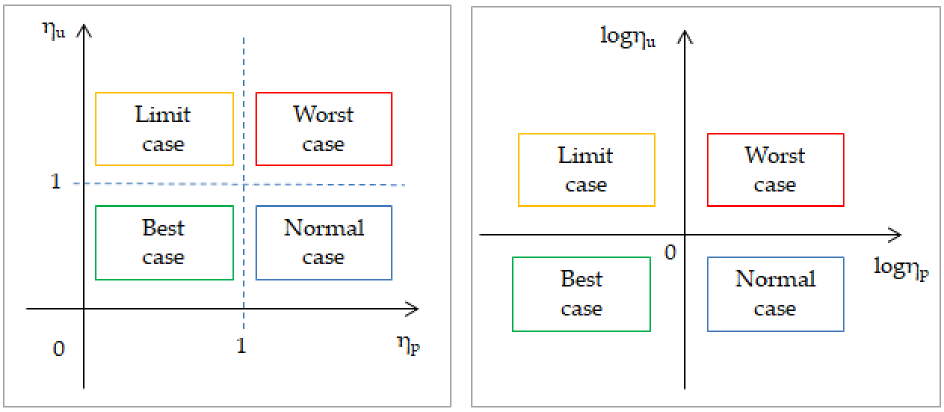


Figure 2.1 Scatter plot graph of use phase efficiency ηu vs production efficiency ηp (on the left) and the corresponding graph in logarithmic scale on the right.

2.4 Case study analysis

2.4.1 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 WFI). 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 a recycling of 89% of the used materials (Gaines and Mintz, 1994). The use phase refers to the scenario 2 of Figure 1, i.e. offsite washing with 20km of transport roundtrip distance (10km+10km).

2.4.2. 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 (Martin et al., 2018);
2. onsitewashing with commercialwashing machines (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_{Y2} with respect to the washing impact $B_{Y2,washing}$ and the transport impact per cup per km $B_{Y2,km}$ according to:

$$n_{km,max} = \frac{X - B_{Y2,washing}}{B_{Y2,km}} \qquad (7)$$

Eq. 7 (rationale in section A.2 of the SI) 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).

2.4.3 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".

2.4.4 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.

In order to analyze EoL scenarios is necessary to analyse distinctly a variation in the EoL of single-use cups and a variation in the EoL of reusable cups. 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. 3), since the use phase efficiency η_u (Eq. 4) does not depend on C_Y or Y_0. Thus, a change in the reusable product EoL, from C_{Y1} to C_{Y2}, induces a variation in the product efficiency according to:

$$\Delta\eta_{p,1\to2} = \eta_{p,2} - \eta_{p,1} = \frac{\Delta Y_{0,1\to2}}{X} = \frac{\Delta C_{Y_{0,1\to2}}}{X} \qquad (8)$$

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 $\Delta C_{Y0,1\to2}$ 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, $\Delta Y_{0,1\to2} = \Delta C_{Y0,1\to2}$. Consequently, if $\Delta C_{Y0,1\to2} > 0 \Rightarrow \eta_{p,2} > \eta_{p,1}$; in other words, as greater the EoL impacts is ($C_{Y0,2} > C_{Y0,1}$), as less efficient the product efficiency is. Finally, a change in C_{Y0} 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 $\Delta C_{X1\to2}$ can be described in terms of a variation of the product efficiency $\Delta\eta_{p,1\to2}$ and the use phase efficiency $\Delta\eta_{u1\to2}$. In this case, both values vary. Indeed, since η_u is inversely proportional with respect to X:

$$\Delta\eta_{u,1\to2} = \eta_{u,2} - \eta_{u,1} = B_Y\left(\frac{1}{X_2} - \frac{1}{X_1}\right) = -B_Y\frac{\Delta C_{X_{1\to2}}}{X_1 X_2} \qquad (9)$$

an increase in the EoL impact for single-use products, $\Delta C_{X1\to2} > 0$, implies a reduction in the use efficiency $\Delta\eta_{u1\to2} < 0$, while $\Delta C_{X1\to2} < 0 \Rightarrow \Delta\eta_{u1\to2} > 0$. The same inversely proportionality holds for the product efficiency, according to

$$\Delta\eta_{p,1\to2} = -Y_0\frac{\Delta C_{X_{1\to2}}}{X_1 X_2} \qquad (10)$$

In terms of environmental BEP n, a change in the use phase efficiency 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 ($X_2 - B_Y$). A detailed discussion of results for these cases goes beyond the scope of this work.

Since a change in sign in n between the two EoL scenarios occurs if and only if (n_1 / n_2) < 0 the ratio

$$\frac{n_1}{n_2} = \frac{Y_1\,(X_2 - B_Y)}{Y_2\,(X_1 - B_Y)} < 0 \Rightarrow \frac{(X_2 - B_Y)}{(X_1 - B_Y)} < 0 \qquad (11)$$

because Y_2; $Y_1 > 0$ by hypothesis.

3. Results

All midpoint impact categories for the production, use and EoL phases are reported in Table 7a, 7b and 7c in section C of the SI.

3.1 Materials analysis

Figure 3 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.

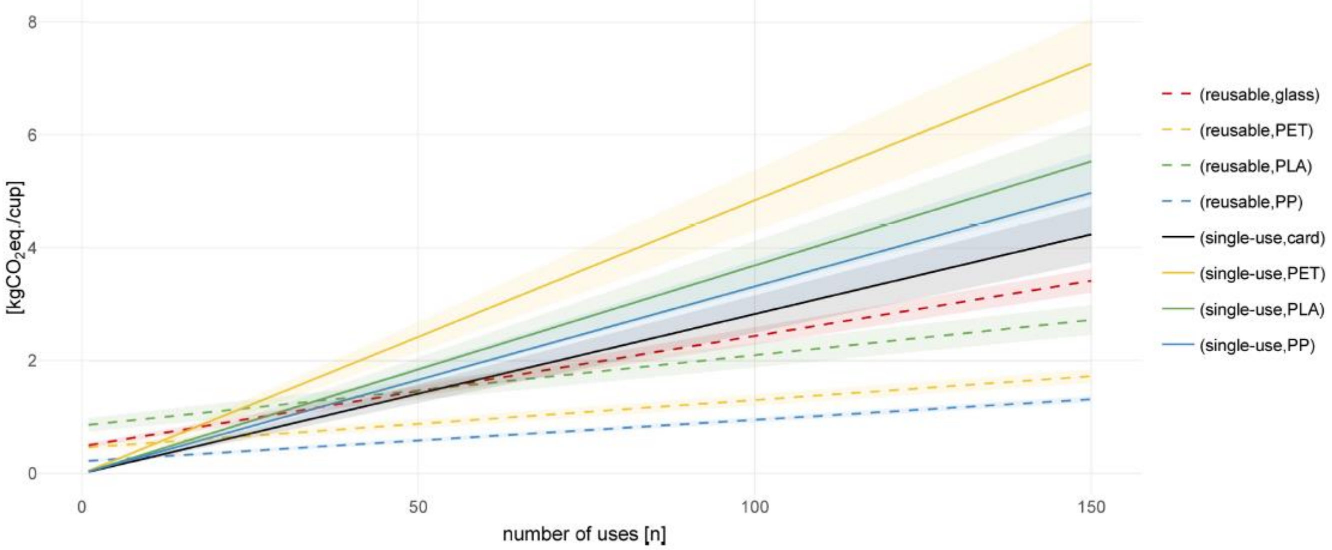


Figure 3. Climate Change (CC) for the offsite washing scenario with a transport distance of 20km during the use phase and energy recovery at EoL for plastic materials and recycling for glass. The shaded areas represent the uncertainty due to the minimum and maximum weights, while the line represent the average ones according to Table 1. Dashed lines refer to the reusable cups while the solid ones refer to the single-use cups.

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 3. 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 1), as a consequence of the carrying capacity during the transport of the use phase. Although the transport noteworthy affects the use phase, all reusable cups achieve the BEP for the CC impact category for less than 50 uses.

Table 3 summarize the BEP for the current section. Next impact categories are presented in Figure 1 in section D.1 of the Supplementary Information. Fig. 1a in the SI 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.

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

Table 3 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.

The best solution with respect to the A impact category (Fig. 1b 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).

With respect to POC impact category (Fig. 1c in the SI) 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 reuses (n > 350).

In terms of eutrophication (E), Fig. 1d in the SI 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. 1e in the SI) 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. 1f in the SI, 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 unique 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 andWSI 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 singleuse 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 (as discussed according to Section 2 according to Table 2), in Figure 2 in section D.1 of the SI, where Fig. 2a shows all results in a unique graph. Figure 4, instead, zooms in 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 analysed 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, 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. 6; indeed, as $\eta_u \rightarrow 1$ (i.e. $B_{x;j} \rightarrow X$), or $\log(\eta_u) \rightarrow 0$, $n \rightarrow \pm\infty$. 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.

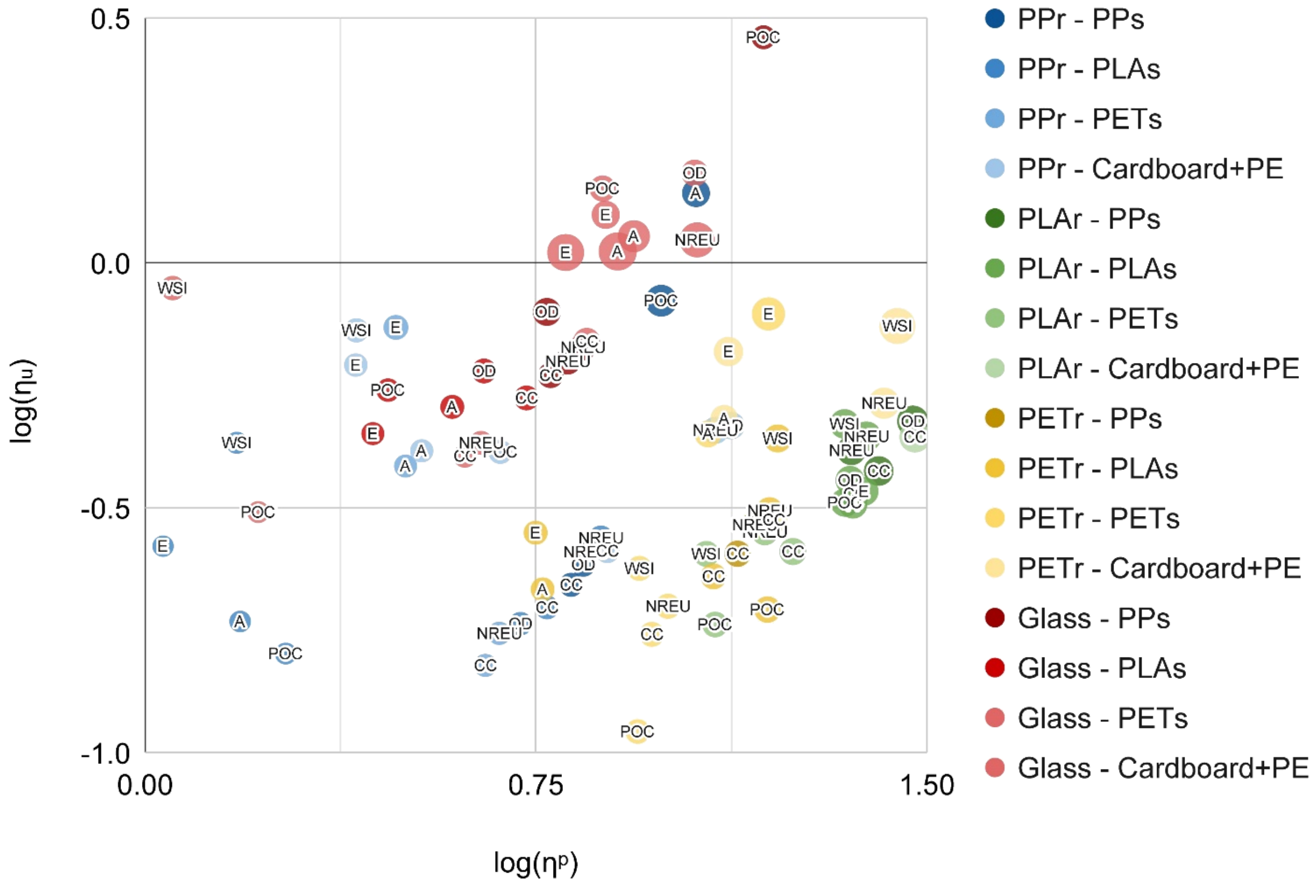


Figure 4: Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$ of the scatter plot of the use efficiency η_u vs the product efficiency η_p related to the material analysis. Midpoint impact categories refer to offsite washing and energy recovery EoL strategy.

3.2. Use phases and transport distance analysis

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 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 graph 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.

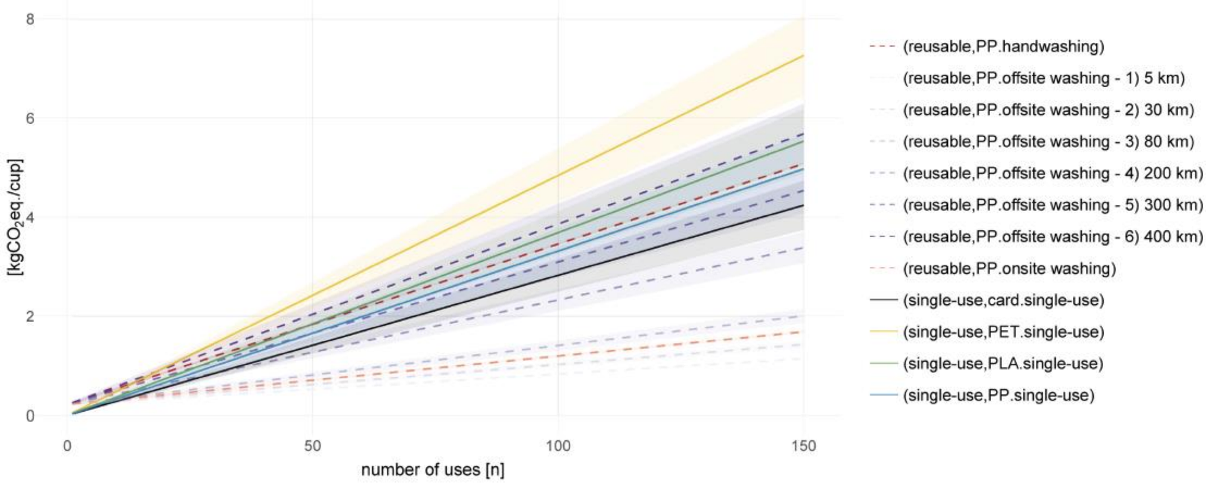


Figure 5. CC of reusable PP cups for onsite handwashing/washing (dashed lines), and offsite washing (dotted lines) VS single-use (continuous lines).

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 4 points out how $n_{km,max}$ is negative, with respect to single-use PP cup, for Acidification, Eutrophication, and WSI midpoint impact categories.

Table 4 Maximum distance [km] for the offsite washing scenarios in the use phase nkm,max, i.e for infinite number of reuse, for plastic reusable cups vs 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				
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
WFI	-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 4 by a scaling factor due to the difference in weight between the cups. For instance, for glass cups the scaling factor, according to Table 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 nonnegative values in Table 4, is much lower, i.e. less than 15km.

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 analyse the different use phases. Results, in terms of use (η_u) and product efficiency (η_p) are plotted in Figure 3 in section D.2 of the SI. Figure 6 presents the zoom for the range $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$. Colours represent the comparison between a different couple of materials (e.g. reusable PP cups vs PLA single-use cups) while the colour 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).

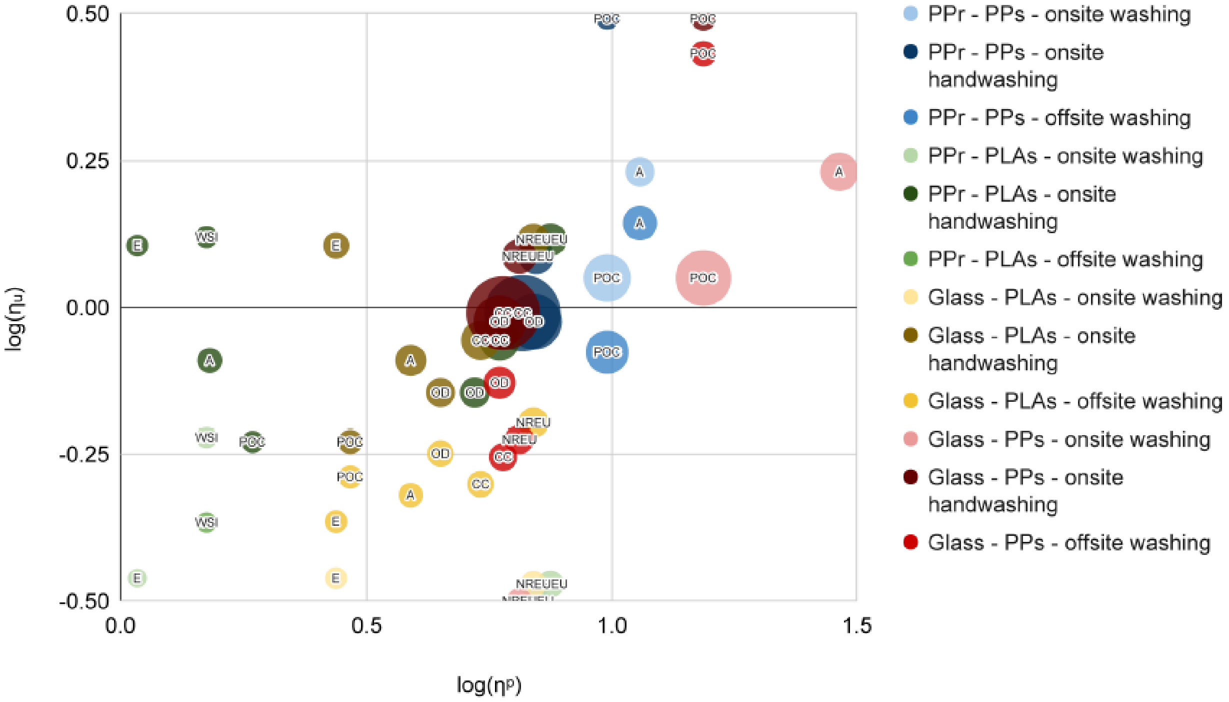


Figure 1. Zoom for $-0.5 < \eta u < 0.5$ and $0 < \eta p < 1.5$ of the scatter plot (log scale) of the use efficiency ηu vs the product efficiency ηp with different use phases. The acronyms CC, OD, A, POC, E, NREU, and WSI represent respectively: global warming, ozone depletion, acidification, photochemical oxidant creation, eutrophication, non renewable energy use, and, water scarcity indicator impact categories.

Dispersion Rate

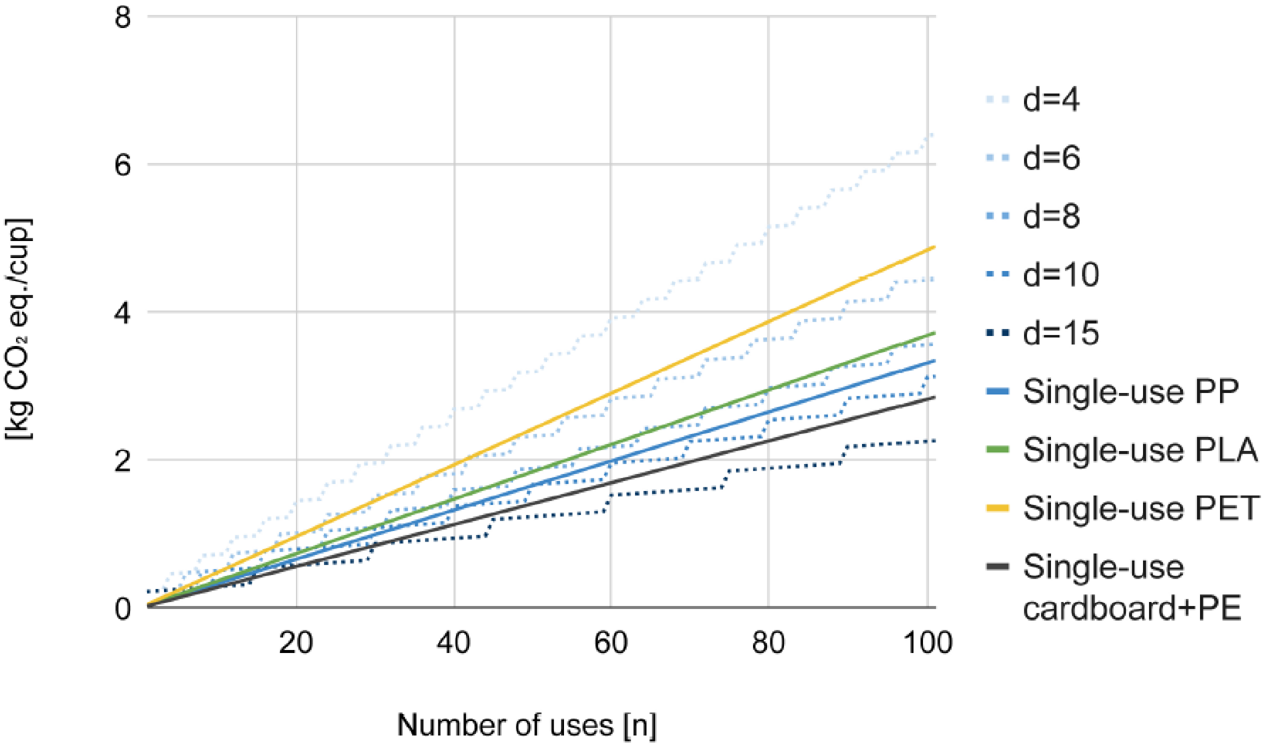


Figure 7: CC of reusable PP cups for offsite washing (dotted lines) vs single-use (continuous lines) with different dispersion rate.

Figure 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 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 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 $d = 4$) the environmental BEP is never reached, for $d >> n$ (e.g. $d = 15$ in Fig. 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. 7).

3.4. EoL scenarios: recycling vs energy recovering

In order to show the rationale of the proposed methodology Table 8a in section D.3 of the SI summarizes the EoL environmental impact variations between the two EoL scenarios (recycling vs energy recovering) for PP and PET singleuse and reusable products. For the PLA cups, composting has been considered instead of recycling. Table 8a shows how recycling is always better than energy recovery for reusable cups, in terms of CC since $\Delta CY_{0,1\rightarrow 2} < 0$, 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 worst for all midpoint impact categories (excluding CC) than energy recovery. 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. $\Delta C_{X\ 1\rightarrow 2} < 0$, both the product and the use phase efficiency are negatively affected.

Finally, Table 8b and 8c 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.

Thus, Table 8b and 8c show that by comparing recycling C_{X2} with energy recovery C_{X1} strategy for single-use in 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 (Table 8b) 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 either for the CC.

4. 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). In next subsections, findings of the present work are compared with previous studies, highlighting and discussing limitations and advantages of the proposed methodology.

4.1. 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, van der Harst and Potting (2013) compared ten disposable cups, showing that, due to the different methodological choices and differences in legislative rules, it was not feasible a reliable comparison. 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 cases is always better neither at small nor large events. Garrido and Del Castillo (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 and Del Castillo (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 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 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 van der 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 washing) 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 eco-design 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 and Gheewala (2020); as reported in this study, the impacts generated by handwashing are considerably lower than those obtained when using a dishwasher. 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 and Gheewala (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.

4.2. Limitations and advantages

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 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.

Cases	**Use efficiency**	**Product efficiency**	**Break-even point**	**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 break-even point
Worst Case	$\eta_u > 1$	$\eta_p > 1$	$n > 0$	1) Improve the use phase to reach a break-even point 2) Improve reusable product production or change material for reusable product

Table 5 Strategy to improve the reusable products impact in order to achieve an environmental benefit for reusable products.

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 both for single-use and reusable products a more complex case arises for the product efficiency η_p. Indeed, by defining $\eta_{p,1} = (Y_1/X_1)$ and $\eta_{p,2} = (Y_2/X_2)$, the variation in the product efficiency depends on a mixed comparison of impacts of reusable and single-use products, according to

$$\Delta\eta_{p,1\rightarrow 2} = \frac{X_1 Y_2 - Y_1 X_2}{X_1 X_2} \qquad (12)$$

Since $X_1, X_2 > 0$ by hypothesis, Eq. 12 means that

$$\Delta\eta_{p,1\rightarrow 2} > 0 \Rightarrow \frac{X_1}{X_2} > \frac{Y_1}{Y_2} \qquad (13)$$

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.

5. 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 (BEP) (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 three use phase strategies for reusable cups (onsite handwashing, onsite washing and offsite washing).

Considering offsite washing use phase - i.e. transport distance of 20km and industrial washing machines - and energy recovery EoL phase, 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 solutions due to transport during the use phase. Generally, reusable cups 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 impact categories. Excluding also POC impact category with respect to PP single-use cups, in all the other cases a break-even point is always 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 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 breakeven 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.

Disclosure statement

No potential conflicts of interests were reported by the authors.

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Supplementary Information

A Proof of the formulas

A.1 Environmental break-even point

The *Environmental break-even point* is calculated as:

$$n_j = \frac{A_Y + C_Y}{X - B_{Y_j}} = \frac{Y_0}{X - B_{Y_j}} \tag{1}$$

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 1 can be simply proofed by declaring X_n, i.e. the impact of n_j single-use plastic products, as

$$X_n = n_j X = n_j \left(A_X + B_X + C_X\right) \tag{2}$$

and $Y_{n,j}$, the impact of a reusable product after n_j reuses for the use scenario j according to

$$Y_{n,j} = A_Y + n_j B_{Y_j} + C_Y \tag{3}$$

Then, by balancing the impact of n uses for both the single-use (Eq. 2) and the reusable product (Eq. 3)

$$X_n = Y_{n_j} \Rightarrow n_j X = A_Y + n_j B_{Y_j} + C_Y \tag{4}$$

equation 1 is proofed.

A.2 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:

$$B_{Y_2} = B_{Y_{2,washing}} + B_{Y_{2,transport}} = B_{Y_{2,washing}} + n_{km} B_{Y_{2,km}} \tag{5}$$

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,

$$\eta_u = \frac{B_{Y_2}}{X} = \frac{B_{Y_{2,washing}} + n_{km,max} B_{Y_{2,km}}}{X} = 1 \tag{6}$$

the maximum number of allowed km $n_{km,max}$ is:

$$n_{km,max} = \frac{X - B_{Y_{2,washing}}}{B_{Y_{2,km}}} \tag{7}$$

B Life Cycle Inventory data

B.1 Data sources

Life cycle phase	Sub-phase process	PP	PLA	PET	Glass	Cardboard +PE coat
Production	Cradle to gate	1	2	1	5	3
	Trasport of resin + cup production	3; 5	3; 5	10; 5		
	Priniting	3	3	3	12	3
	Packaging	3	3	3	3	3
	Transport from production site to city of use	11	11	11	11	11
Use	Onsite handwashing	7	7	7	7	-
	Onsite washing	7	7	7	7	-
	Offsite washing	8	8	8	8	-
	Transport to location of use	9	9	9	9	9
EoL	Transport to location of EoL	13	13	13	13	13
	EOL packaging	3	3	3	3	3
	Incineration	3	3	3	-	3
	Composting	-	3	-	-	-
	Recycling	4	-	4	6	-

Table 1: List of all data sources for all materials and life cycle phases. The numbers within the table refer to: (1) impact values directly taken from PlasticsEurope (Plastics Europe, 2020), (2) inputs/outputs values taken from Vink et al. (2007), (3) inputs/outputs values taken from Vercalsteren et al. (2007), (4) inputs/outputs values taken from ERG report (Franklin Associates, 2018), (5) Ecoinvent database, (6) inputs/outputs values taken from Gaines and Mintz (1994), (7) inputs/outputs values taken from Martin, Bunsen, and Ciroth (2018), (8) inputs/outputs values taken from an analysis carried out on behalf of an Italian crockery washing company, (9) modeled by authors, (10) approximation based on Vercalsteren et al. (2007) taking into account the physical-chemical properties of the material, (11) modeled by authors, (12) same as cardboard, no direct information, (13) modeled by authors.

B.2 Production phase

Sub-phase process	**Inventory data for 1kg of:**	**Single-use PP**	**Single-use PLA**	**Single-use PET**	**Cardboard + PE coat**
Cradle to gate	PP resin (g)	1010	-	-	-
	PLA pellets	-	*	-	-
	PET bottle grade (g)	-	-	1010	-
	Packaging film, low density polyethylene {RER} - production (g)	-	–	-	54.27
	Solid bleached board {RER} - production (g)	-	-	-	1031
Transport of resin	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} - transport, freight, lorry 16-32 metric ton, EURO6 (tkm)	0.101	0.101	0.101	0.108
Cup production	PP/PET resin; PLA pellets (g)	1010	1010	1010	
	Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	1.21	0.93	1.9	1.3
	Process. (1) Thermoforming of plastic sheets {FR} - processing (2) Injection moulding {RER} - processing	(1)	(1)	(1)	
	Paper waste	-	-	-	84.5
Printing	Printing ink, offset, without solvent, in 47.5% solution state {RER} - printing ink production, offset, product in 47.5% solution state (g)	0.032	0.032	0.032	0.13
Packaging	VOC (g)	-	-	-	0.19
	Packaging film, low density polyethylene {RER} - production (g)	33.6	17.6	33.6	50.4
	Corrugated board box {RER} - production (g)	224	256.4	224	335.6
	Electricity, low voltage {Europe without Switzerland} - market group for	0.018	0.018	0.018	0.018
Transport from production site to city of use	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} - transport, freight, lorry 16-32 metric ton, EURO6 (tkm)	1	1	1	1

* inventory data from Vink et al. (2007).

Table 2: Inventory data for the production phases for the single-use cups. All the data refer to the weight of 1 kg of cups.

Sub-phase process	**Inventory data for 1kg of:**	**Reusable PP**	**Reusable PLA**	**Reusable PET**	**Glass cup**
Cradle to gate	PP resin (g) PLA pellets	1010 -	- *	- -	Packaging glass, white {RER w/o CH+DE} - production - Alloc Def, U
	PET bottle grade (g)	-	-	1010	
	Packaging film, low density polyethylene {RER} - production (g)	-	-	-	
	Solid bleached board {RER} - production (g)	-	-	-	
Transport of resin	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} - transport, freight, lorry 16-32 metric ton, EURO6 (tkm)	0.101	0.101	0.101	

Sub-phase process	Inventory data for 1kg of:	Reusable PP	Reusable PLA	Reusable PET	Glass cup
Cup production	PP/PET resin; PLA pellets (g)	1010	1010	1010	
	Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	2.5	1.9	4	
	Process. (1) Thermoforming of plastic sheets {FR} - processing (2) Injection moulding {RER} - processing	(2)	(2)	(2)	
	Paper waste	-	-	-	
Printing	Printing ink, offset, without solvent, in 47.5% solution state {RER} - printing ink production, offset, product in 47.5% solution state (g)	0.032	0.032	0.032	0.13
	VOC (g)	-	-	-	0.19
Packaging	Packaging film, low density polyethylene {RER}— production (g)	33.6	17.6	33.6	50.4
	Corrugated board box {RER} - production (g)	224	256.4	224	335.6
	Electricity, low voltage {Europe without Switzerland} - market group for	0.018	0.018	0.018	0.018
Transport from production site to city of use	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} - transport, freight, lorry 16-32 metric ton, EURO6 (tkm)	1	1	1	1

Table 3: Inventory data for the production phases for the reusable cups. All the data refer to the weight of 1 kg of cups.

B.3 Use phase

Inventory data for the use phase	Offsite washing	Onsite washing	Onsite handwashing
Tap water {Europe without Switzerland} - tap water production, conventional treatment (kg)	0.23	0.14	0.5
Soap {RER} - production	0.13	0.7	0.5
Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	0.01	0.014	0.061
Wastewater, average {CH} - treatment of, capacity 5E9l/year (m^3)	0.00023	0.00014	0.0005
Transport, freight, light commercial vehicle {Europe without Switzerland} - processing (tkm)	0.02	-	-
Carboxymethyl cellulose, powder {RER} - production (g)	0.07	-	-
Fatty alcohol sulfate {RER} - production, coconut oil (g)	-	0.035	-
Polycarboxylates, 40% active substance {RER} - production (g)	-	0.035	-
Sodium phosphate {RER} - production (g)	-	0.035	-
Sodium perborate, monohydrate, powder {RER} - production (g)	-	0.105	-

Inventory data for the use phase	**Offsite washing**	**Onsite washing**	**Onsite handwashing**
Alkylbenzene sulfonate, linear, petrochemical {RER} - production (g)	-	-	0.0675
Sodium hydroxide, without water, in 50% solution state {RER} - chlor-alkali electrolysis, diaphragm cell (g)	-	-	0.01985
Water, completely softened, from decarbonised water, at user {RER} - production (g)	-	-	0.365

Table 4: Inventory data for the use phase of the reusable cups; all data refer to 1 single reusable cup. The transport value refers to the transport of 1 kg of cups.

B.4 EoL phase

Sub-phase process	Inventory data for 1 kg of:	PP cup	PLA cup	PET cup	Glass cup	Cardboard +PE cup
Transport to location of EoL	Municipal waste collection service by 21 metric ton lorry {CH} - processing (tkm)	0.015	0.015	0.015	0.015	0.015
EOL packaging	Municipal solid waste {CH} - treatment of, incineration (g)	33.6	17.16	33.6	50.4	50.4
	Paper (waste treatment) {GLO} - recycling of paper (g)	224	256.4	224	335.6	335.6
Incineration	Heat, district or industrial, other than natural gas {Europe without Switzerland} - heat production, heavy fuel oil, at industrial furnace 1MW (MJ)	0.169	0.169	0.169	-	0.169
	Heat, district or industrial, natural gas {Europe without Switzerland} - heat production, natural gas, at industrial furnace low-NOx > 100kW (MJ)	0.289	0.289	0.289	-	0.289
	Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	0.085	0.085	0.085	-	0.085
	Process-specific burdens, residual material landfill {CH} - processing (kg)	0.0009	0.0009	0.0009	-	0.118
	Emissions to air	see Table 6	see Table 6	see Table 6	-	see Table 6
	Energy output: Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	2.235	1.017	1.117	-	0.782
Composting	Wood chips, from post-consumer wood, measured as dry mass {CH} - treatment of waste wood, post-consumer, sorting and shredding (kg)	-	0.175	-	-	-
	Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	-	0.032	-	-	-
	Process-specific burdens, municipal waste incineration {CH} - processing (kg)	-	0.0197	-	-	-
	Emission to air NH_3 (g)	-	0.02	-	-	-
	Emission to air CH_4 (kg)	-	0.00024	-	-	-
	Emission to air N_2O (g)	-	0.096	-	-	-
Recycling	Sodium hydroxide, without water, in 50% solution state {RER} - chlor-alkali electrolysis, mercury cell (kg)	$6.9x10^{-04}$	-	0.0095	-	-
	Soap {RER} - production (kg)	0.0017	-	0.0027	-	-
	Silicone product {RER} - production (kg)	0.0015	-	0.0031	-	-
	Tap water {Europe without Switzerland} -tap water production, conventional treatment (kg)	1.03	-	0.88	-	-
	Natural gas, low pressure {CH} - natural gas pressure reduction from high to low pressure (m^3)	0.026	-	0.0068	$3.3x10^{-06}$	-
	Diesel {Europe without Switzerland} - petroleum refinery operation (kg)	0.002284	-	0.002249	0.0016	-
	Liquefied petroleum gas {Europe without Switzerland} - petroleum refinery operation (kg)	$7.43x10^{-06}$	-	$8.52x10^{-06}$	$6.26x10^{-06}$	-

Sub-phase process	Inventory data for 1 kg of:	PP cup	PLA cup	PET cup	Glass cup	Cardboard +PE cup
	Transport, freight, lorry 16-32 metric ton, EURO6 {RER} - transport, freight, lorry 16-32 metric ton, EURO6 (tkm)	0.1	-	0.1	-	-
	Electricity, low voltage {Europe without Switzerland} - market group for (kWh)	0.53	-	0.82	0.085	-
	Iron (III) chloride, without water, in 40% solution state {CH} - iron (III) chloride production, product in 40% solution state (kg)	-	-	$6.8x10^{-05}$	-	-
	Hydrogen peroxide, without water, in 50% solution state {RER} - hydrogen peroxide production, product in 50% solution state (kg)	-	-	$5.4x10^{-06}$	-	-
	Sulfuric acid {RER} - production (kg)	-	-	0.0010	-	-
	Sodium chloride, powder {RER} - production (kg)	-	-	$4.8x10^{-04}$	-	-
	Propane {GLO} - extraction, from liquefied petroleum gas (kg)	-	-	$1.6x10^{-05}$	-	-
	Nitrogen, liquid {RER} - air separation, cryogenic (kg)	-	-	0.0038	-	-
	BOD5 (kg)	$5.5x10^{-06}$	-	0.0018	-	-
	COD (kg)	$2.5x10^{-04}$	-	0.0016	-	-
	Suspended solid (kg)	$2.0x10^{-04}$	-	$7.8x10^{-04}$	-	-
	Municipal solid waste (kg)	0.19	-	0.19	-	-
	output: Polypropylene, granulate {RER} - production (kg)	0.85	-	-	-	-
	Solid (kg)	-	-	$3.6x10^{-05}$	-	-
	output: Polyethylene terephthalate, granulate, amorphous {RER} - production (kg)	-	-	0.85	-	-
	output: Packaging glass, green {RER w/o CH+DE} - production (kg)	-	-	-	0.89	-

Table 5: Inventory data for the end of life phases of the cups grouped for material used. All data refer to the weight of 1 kg of cups.

B.5 Incineration

Emission to air for 1kg of:	**PP cup**	**PLA cup**	**PET cup**	**Cardboard +PE cup**
CO_2 (kg)	3.08	1.81	2.27	1.45
NOx (kg)	4.24×10^{-04}	4.24×10^{-04}	4.24×10^{-04}	4.24×10^{-04}
SO_2 (kg)	2.70×10^{-05}	2.70×10^{-05}	2.70×10^{-05}	2.70×10^{-05}
PM (kg)	1.20×10^{-05}	1.20×10^{-05}	1.20×10^{-05}	1.20×10^{-05}
CO (kg)	5.00×10^{-06}	5.00×10^{-06}	5.00×10^{-06}	5.0×10^{-06}
As (kg)	3.29×10^{-09}	/	3.29×10^{-09}	3.29×10^{-09}
Cd (kg)	2.13×10^{-07}	/	2.13×10^{-07}	2.13×10^{-07}
Cr (kg)	1.30×10^{-06}	/	1.30×10^{-06}	2.63×10^{-07}
Pb (kg)	5.44×10^{-06}	/	5.44×10^{-06}	7.55×10^{-07}
Ni (kg)	5.03×10^{-07}	/	5.03×10^{-07}	1.69×10^{-07}
Hg (kg)	7.23×10^{-09}	/	7.23×10^{-09}	1.98×10^{-08}
Dioxins (kg)	1.80×10^{-13}	1.80×10^{-13}	1.80×10^{-13}	1.80×10^{-13}

Table 6: Emission to air, produced during the incineration process.

C Midpoint impact categories

Midpoint impact category		A_Y				$C_{Y,1}$ (Energy recovery)				$C_{Y,2}$ (Recycling)			
Acronym	**Unit of measure**	**PP**	**PLA**	**PET**	**Glass**	**PP**	**PLA**	**PET**	**Glass**	**PP**	**PLA**	**PET**	**Glass**
CC	kg CO_2 eq./cup	0.137	0.608	0.331	0.480	0.081	0.240	0.124	-	-0.061	-0.004	-0.144	-0.281
OD	g CFC-11 eq./cup	$0.314x10^{-4}$	$1.229x10^{-4}$	$12.825x10^{-4}$	$0.632x10^{-4}$	$-0.048x10^{-4}$	$-0.087x10^{-4}$	$-0.039x10^{-4}$	-	$0.018x10^{-4}$	$-0.005x10^{-4}$	$-0.031x10^{-4}$	$-0.405x10^{-4}$
A	g SO_2 eq./cup	0.481	4.599	1.239	3.224	-0.197	-0.353	-0.161	-	-0.197	-0.048	-0.619	-2.501
POC	g Ethene eq./cup	0.033	0.295	0.205	0.138	-0.010	-0.018	-0.008	-	-0.015	-0.002	-0.040	-0.101
E	g PO_4 eq./cup	0.225	2.236	0.580	0.584	-0.136	-0.261	-0.116	-	0.008	-0.019	-0.126	-0.358
NREU	MJ/cup	4.521	13.432	8.450	8.043	-0.862	-1.602	-0.739	-	-2.712	-0.065	-4.235	-4.665
WSI	m^3/cup	$0.057x10^{-2}$	$0.560x10^{-2}$	$0.401x10^{-2}$	$0.159x10^{-2}$	$-0.023x10^{-2}$	$-0.054x10^{-2}$	$-0.024x10^{-2}$	-	$-0.020x10^{-2}$	$-0.023x10^{-2}$	$-0.283x10^{-2}$	$-0.144x10^{-2}$

(a) Values per unit adopted for production and EoL phases for the reusable cups

Midpoint impact category		A_X				$C_{X,1}$ (Energy recovery)				$C_{X,2}$ (Recycling)			
Acronym	**Unit of Measure**	**PP**	**PLA**	**PET**	**Cardboard**	**PP**	**PLA**	**PET**	**Cardboard**	**PP**	**PLA**	**PET**	**Cardboard**
CC	kg CO_2 eq./cup	0.019	0.025	0.033	0.019	0.014	0.012	0.016	0.010	-0.011	0.000	-0.018	-
OD	g CFC-11 eq./cup	$0.468x10^{-5}$	$0.549x10^{-5}$	$16.342x10^{-5}$	$0.231x10^{-5}$	$-0.084x10^{-5}$	$-0.042x10^{-5}$	$-0.050x10^{-5}$	$-0.031x10^{-5}$	$0.032x10^{-5}$	$-0.002x10^{-5}$	$-0.040x10^{-5}$	-
A	g SO_2 eq./cup	0.059	0.203	0.110	0.096	-0.035	-0.017	-0.021	-0.013	-0.035	-0.002	-0.080	-
POC	g Ethene eq./cup	0.004	0.013	0.023	0.006	-0.002	-0.001	-0.001	-0.001	-0.003	0.000	-0.005	-
E	g PO_4 eq./cup	0.025	0.095	0.044	0.045	-0.024	-0.013	-0.015	-0.010	0.001	-0.001	-0.016	-
NREU	MJ/cup	0.673	0.566	0.860	0.353	-0.151	-0.078	-0.095	-0.058	-0.475	-0.003	-0.544	-
WSI	m^3/cup	$0.064x10^{-3}$	$0.256x10^{-3}$	$0.455x10^{-3}$	$0.159x10^{-3}$	$-0.039x10^{-3}$	$-0.026x10^{-3}$	$-0.031x10^{-3}$	$-0.023x10^{-3}$	$-0.035x10^{-3}$	$-0.011x10^{-3}$	$-0.363x10^{-3}$	-

(b) Values per unit adopted for the production and EoL phases for the single-use cups

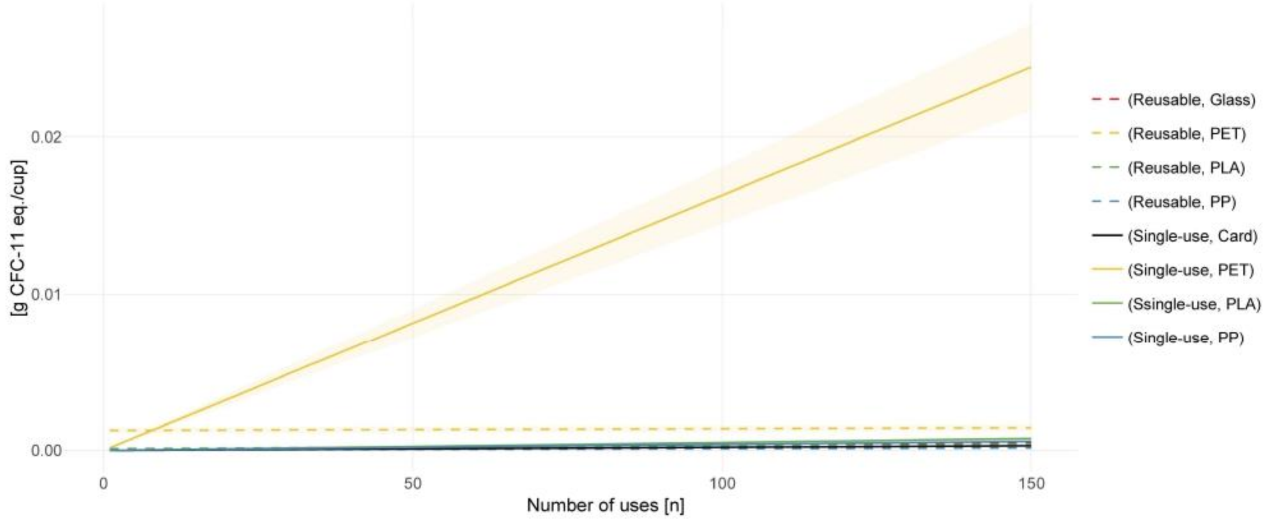
Midpoint impact category	Unit of Measure	$B_{Y,1}$ (Onsite washing)	$B_{Y,3}$ (Onsite handwashing)	$B_{Y,2,washing}$ (Offsite washing)	Unit of Measure	$B_{Y,2,km}$ (Transport)
CC	kg CO_2 eq./cup	0.010	0.032	0.006	kg CO_2 eq./g/km	$0.019x10^{-4}$
OD	g CFC-11 eq./cup	$0.010x10^{-4}$	$0.036x10^{-4}$	$0.007x10^{-4}$	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

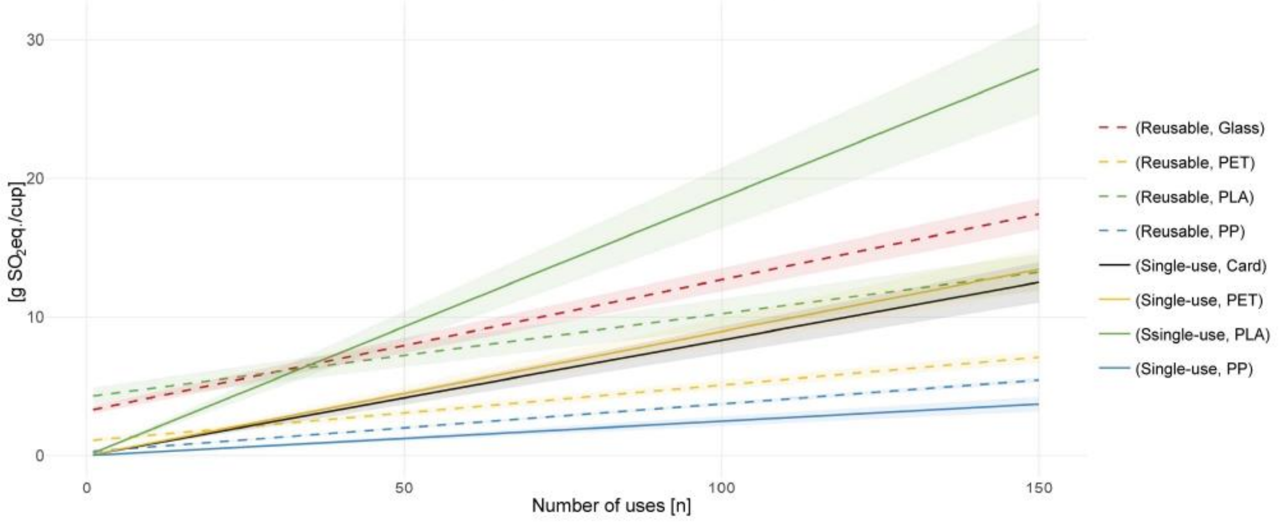
Table 7: Midpoint impact categories for the production and EoL phase for reusable cups (Fig. 7a) and single-use (Fig. 7b), and for the use phase for reusable cups (Fig. 7c) for the different analyzed scenarios.

D Results interpretation

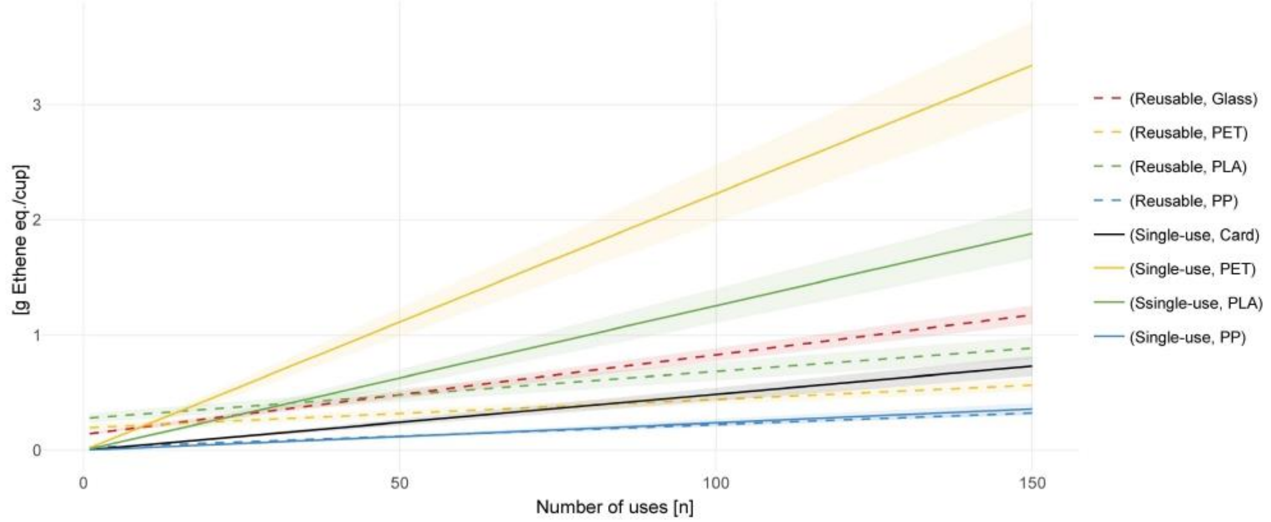
D.1 Materials analysis



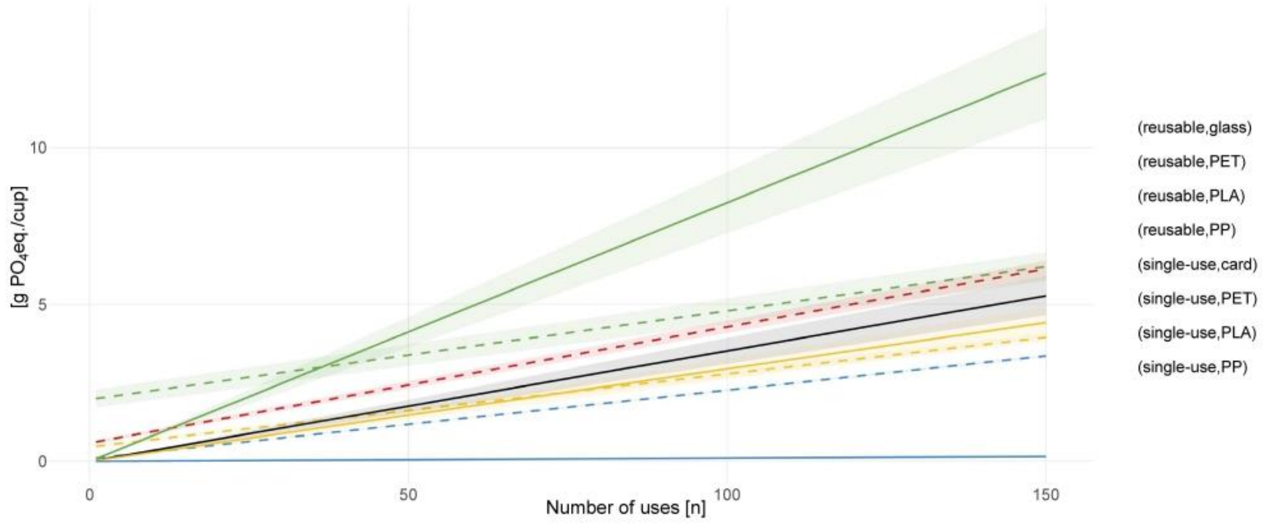
(a) Ozone Depletion (OD)



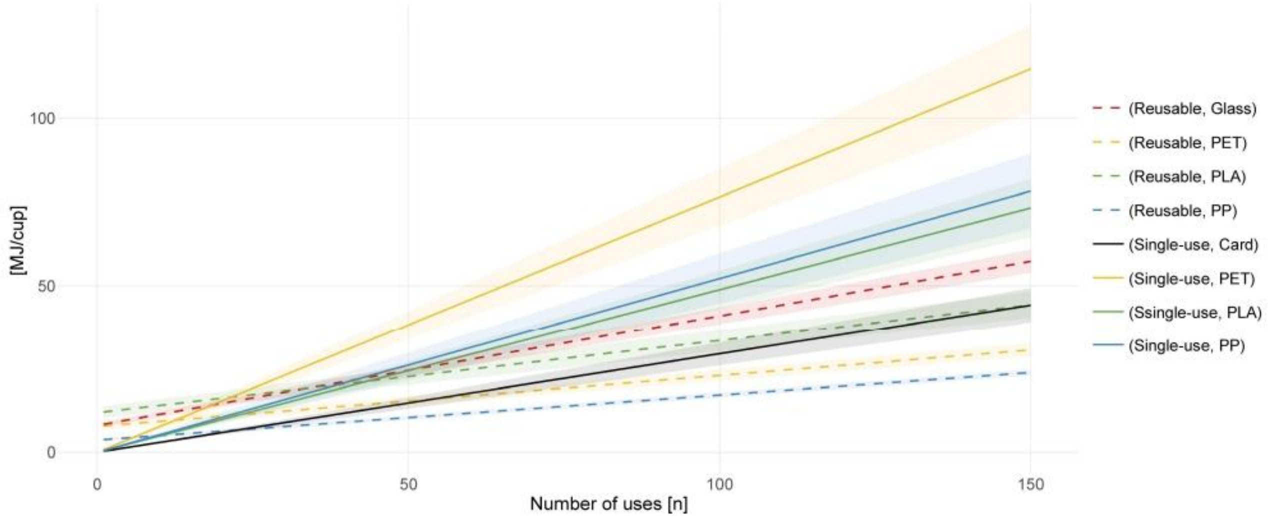
(b) Acidification (A)



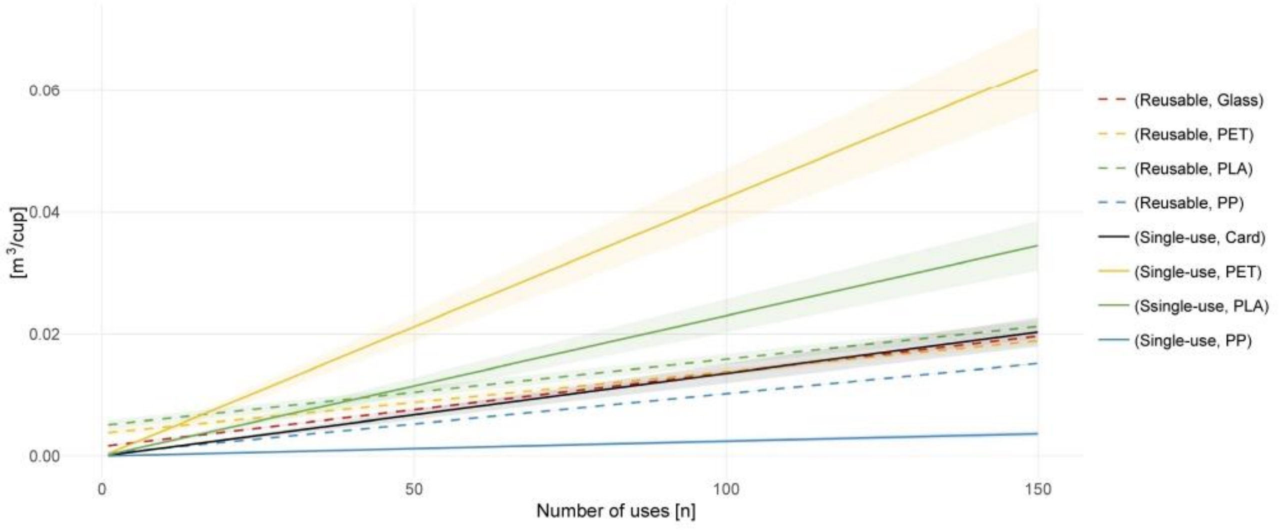
(c) Photochemical ozone creation (POC)



(d) Eutrophication (E)

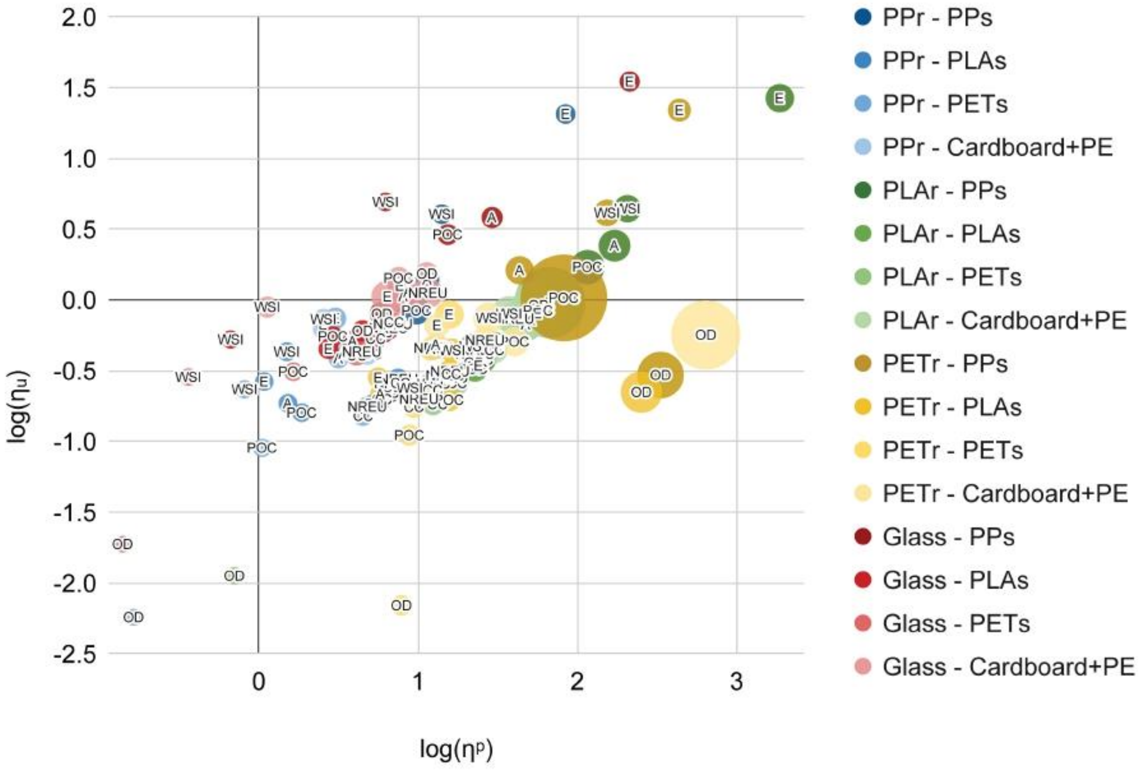


(e) Non-Renewable Energy Use (NREU)

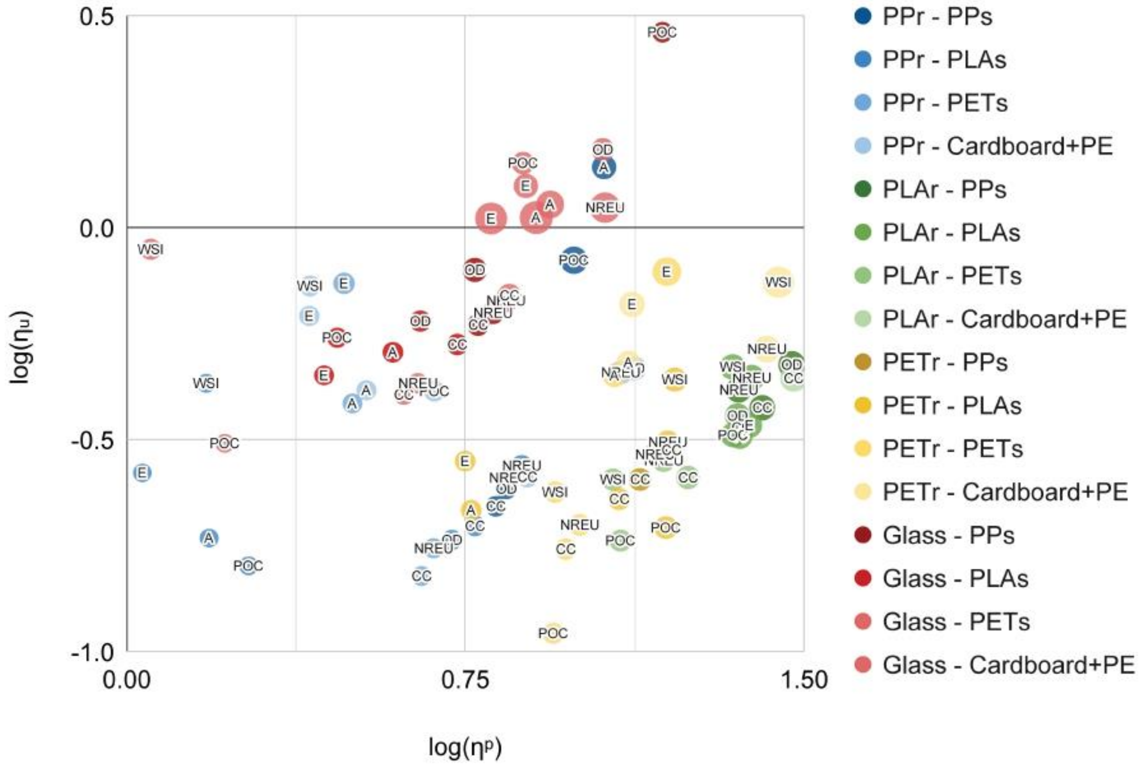


(f) Water Scarcity Indicator (WSI)

Figure 1: Reusable vs single-use cups 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.



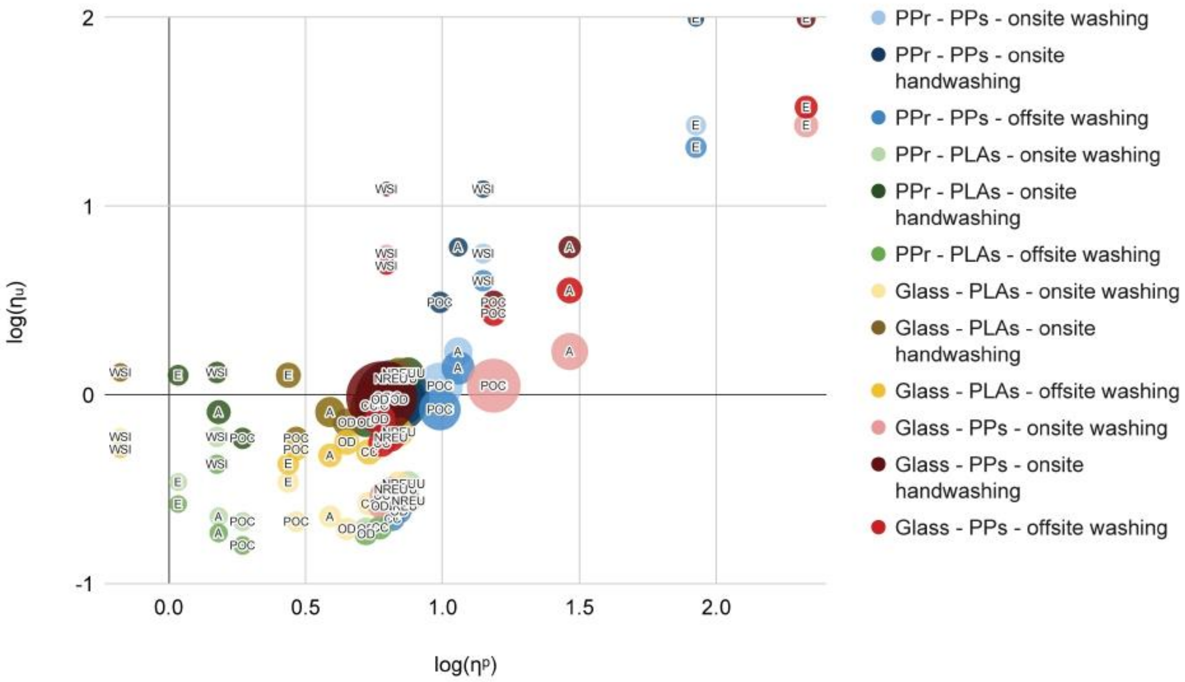
(a) All data



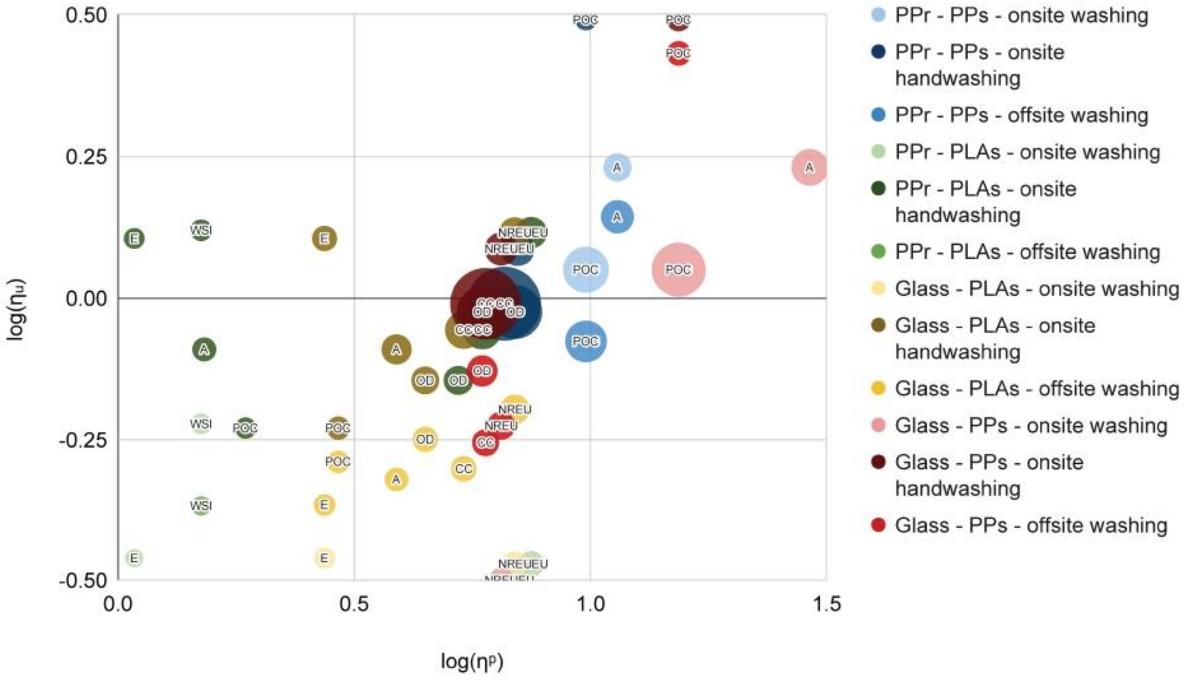
(b) Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$

Figure 2: Scatter plot of the use efficiency η_u vs the product efficiency η_p related to the material analysis. Midpoint impact categories refer to offsite washing and energy recovery EoL strategy.

D.2 Transport distance analysis



(a) All data



(b) Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$

Figure 3: Scatter plot (logarithmic scale) of the use efficiency η_u vs the product efficiency η_p with different use phases. 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

D.3 EoL scenarios comparison

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: EoL scenarios comparison between recycling and energy recovery

Conclusion

The main scope of my research work, mainly presented in this thesis, has been to deeply understand the concept of Circular Economy through an academic and scientific approach. A large part of the scientific community and research around circularity agree that the circular economy enables huge opportunities in terms of growth and prosperity while addressing waste and pollution issues by design. The circular transition can be also seen as an opportunity to evolve current business models, largely currently based on the traditional industrial model of "take-make-dispose", capable to match most of the Sustainable Development Goals and challenges in terms of economic and environmental long-term competitiveness.

The strategic global relevance of the circular economy is also confirmed by the huge commitment coming from public institutions, at the national and international level, as presented, for example, in the European Green Deal Strategy and Next Generation EU Plan, in the National Plan for Recovery and Resilience by the Italian Government or in the latest Five Year Plan policy in China, where the circular economy is a key pillar to guide the industrial agenda and a tool to implement positive development for society in general, besides a strategy to build back better after the pandemic crisis of Covid-19.

In the last few years Circular Economy (CE) is receiving increasing attention worldwide. Moreover, as shown in Chapter 1, during the last couple of years the CE concept has been more researched than ever by academics and researchers. Nevertheless, in my preliminary research, there is no evidence about how this trend impacts different business sectors and, for example, if there is a concentration of research related to specific industries. This is why one of my goals pursued through my research activity has been to map out past and recent studies around the concept of the CE, to identify how the industrial sectors are distributed across the CE literature and, in particular which economic activities are more reviewed and which ones may still need additional scientific research around the concept of CE. The findings are quite interesting, as presented in Chapter 1 of this thesis.

The most represented sectors (cfr. NACE category) in the scientific research landscape is the Manufacture sector, followed by Professional, scientific and technical activities and Electricity, gas, steam, and air conditioning supply. In the Manufacture industry, research findings highlight a specific focus on the *manufacture of coke and refined petroleum products*, *manufacture of food products* and *manufacture of basic metals*. The Coke and oil sector is one of the most impactful for the environment, considering air, soil and water pollution both upstream and downstream. In this field the CE could help innovating the different phases of the value chain - extraction, transport, logistic, refinery and distribution - with the aim to improve the life cycle impacts. Regarding the manufacture of food products, the opportunities connected to CE innovations are well known and already put in practice by many companies. As a big amount of waste is generated during all the different phases of production, harvesting, processing, packaging and logistics, a lot of innovative activities could be developed to improve and transform this strategic sector. Also, in the sector of basic metals there are many opportunities connected to CE both considering the impact of the extraction and production phases and the availability of recycling processes and technologies. A conclusion here can be that new business opportunities, together with the evolution of environmental policy constraints, influence the scientific development, creating right conditions for researcher to develop more knowledge.

Other sectors where a relevant number of research papers has been found are *Manufacture of chemicals and chemical products*, *Manufacture of computer, electronic and optical products*, *Manufacture of textiles*, *Manufacture of wood and of products of wood and cork* and *Manufacture of paper and paper products*. It is quite interesting note that this result reflects the priority recently identified by the European policymakers in the field of CE. In fact, the last EU Circular Economy Action Plan, agreed among the European Commission and the European Parliament in February 2021, aim to focus on sectors that use most resources and where the potential for circularity is higher such as: electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients.

Other sectors like *Wearing apparel in manufacture of textiles*, *Manufacture of leather products*, *Manufacture of furniture* and *Repair and installation of machinery and equipment* are less represented in the scientific research landscape, even if they are virtually quite interesting from the point of view of a circular approach, which could be very interesting in prolonging the life of products or in reshaping existing/new materials.

In general, I believe that scientists and researchers could further develop research around sectors currently less researched, bringing new insights, needs and opportunities to the policymakers, in order to develop transformative policies also in sectors like: real estate management, accommodation services, public administration and defence, financial and insurance activities

As a potential interesting field for future research, it could be interesting to periodically continue with a detailed and updated analysis of the bibliometric research results, in order to obtain new insights and intersectoral relationships. The CE topic is a key strategic point in the sustainable development agenda as of today, so it is likely to expect an increase in the numbers of CE research conducted in a year. Moreover, it could be interesting to match research results with the sectors economic benefit expected by other dedicated research, to have a more complete vision and to support, for example, an investment decision making process.

As presented in several parts of this thesis, scientific research agrees that the circular economy is supported by the transition towards renewable energy sources and circular business models following usually three simple principles: design out of waste and pollution, keep products and materials in use and regenerate natural systems. Such a framework needs new business applications to face the challenge on materials' transition, i.e. from single use to reuse in the plastic industry. In fact, despite the huge effort of practitioners and academic researchers in investigating innovative solutions to increase plastic recycling efficiency, as well as the commitment of policymakers to adopt new policies and strategies, the recycling rate, for example, in EU is still far to be considered satisfactory.

In Chapter 2, an innovative business model for an urban integrated system, related to the end-of-life management in plastic issue, has been presented - aiming at transforming material flows into material stocks. The model allows private companies (food and drink providers) to reduce the usage of single-use products and the amount of exploited raw materials. A pilot project, focused on the reduction of single-use plastic cups, has been also discussed in order to have practicable evidences to analyze; the business model is based on a service company that introduced a Deposit-Return System (DRS) for reusable plastic cups within the urban area of the City of Turin. The integrated system aims at reducing the splitting of the material flow, i.e. the plastic cups, by aggregating them into a new material stock. In conclusion, it is clear that a deposit system, for the management of plastic cups in the food and drink retail providers, increases the life of each cup from few minutes to years, by stacking the flow of materials and transforming a constant flow of materials made by single-use products into a, temporary (a few years), stock of materials. The case study has been validated by a survey related to 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 dispose 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.

Indeed, the production of reusable cups need 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 squanders a large amount of water. Second, current plastic cups producers are selling products, i.e. reusable cups, only tested, in a large scale, during temporary, from a few days up to a few weeks' large festival. Thus, the effective durability of a reusable cup is still to be assessed within the daily life of a bar. It is clear that within bars, restaurant and clubs of a city the usage is much more intensive with respect to a time-limited event. Finally, eventually 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 simpler 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 within the city, it may be possible to collect current unavailable data on several social phenomena related to the nightlife.

Even if, survey's results and preliminary outcome from the pilot project are satisfactory several aspects have to be further investigated. First, a Life-Cycle Assessment needs to be conducted in order to compare classical single-use container DRS with the proposed DRS for reusable cups and to identify possible inefficiency, from an environmental point of view, and to reveal the "environmental break-even point".

Therefore, I decided to be part of a novel research, presented in Chapter 3 of this thesis.

Research in Chapter 3 introduce 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 (BEP).

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 three use phase strategies for reusable cups (onsite handwashing, onsite washing and offsite washing).

Considering offsite washing use phase - i.e. transport distance of 20km and industrial washing machines - and energy recovery End-of-Life phase, 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 and where (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.

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 solutions due to transport during the use phase. Generally, reusable cups 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 accomplished for all impact categories. Excluding also POC impact category with respect to PP single-use cups, in all the other cases a break-even point is always 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 implementing this method based on the environmental BEP, a standard functional unit for the product and use efficiency, i.e. one single-use, can be used, simplifying evaluations among LCA studies. Within the current transition to the circular economy, the 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.

To conclude, climate change is an extremely relevant phenomenon whose consequences are not only limited to the environment but have major effects also for the economic and social dynamics of present and future generations. As a systemic solution, the Circular Economy is vital to solve the climate crisis, and moreover to put the basis for a long-lasting economic development that generates wealth reconnecting business and society.

The current linear model of "take, make, dispose" embeds critical risks for businesses, such as high exposure to price volatility for natural resources or regulations to reduce pollution and carbon dioxide emissions. These risks then scale to a systemic level through today's industrial processes. On the contrary, the Circular Economy can mitigate linear risks and create opportunities in terms of resource efficiency and profitability gains. Companies that shift towards a circular model have the potential to increase their competitiveness in the medium to long term, becoming more appealing to financial institutions in terms of funding and financial support. In this logic, for example, it is worth mentioning the white paper published in 2021 by the Ellen MacArthur Foundation, which clearly shows that the circular economy has a de-risking effect and drives superior risk-adjusted returns for investors and financial institutions.

The pandemic started in 2020 and the blocking measures required have certainly revealed with greater evidence and urgency the exposure of our economic and social system to a series of risks of global nature, and the severe economic recession that has followed requires a profound collective effort to reshape our economy.

The spread of Covid-19 has therefore redesigned the challenges related to sustainability and accelerated the need for new paradigms. This is linked to the exponential growth of interest by economic operators, investors, consumers and regulators in environmental, social and governance dimensions of the new economy that is to be built in the phase of post-pandemic restart. In fact, as we rise to the challenges caused by the coronavirus pandemic, the question is no longer should we build back better, but how.

A well-known proverb said "If you want to go fast, go alone. If you want to go far, go together" – this is true, more than ever, for such an ambitious and systemic transition. To deliver the economic, environmental and social impacts expected by the Circular Economy at scale, businesses and governments must work together.

As a general perspective for the future, considering also the role of the "Innovation for the Circular Economy" Industrial Ph.D. and its connection with the world of business (in my case: the financial services industry), I strongly believe two aspects can be highlighted that would be worth exploring in terms of academic research and business implications: i) the role of finance and ii) the role of open innovation to evolve business models in the private sectors, both as unique enabling combination in accelerating the circular economy transition.

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I want to thank me for doing all this hard work,
never quitting and just being me at all times.

Calvin Cordozar Broadus Jr.