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Developing an Instrument to Measure the Degree of Product Circularity

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Abstract

The circular economy has recently emerged as a possible alternative to the linear economic model based on the *take-make-dispose* paradigm. The circular economy might be a promising solution to the increasing environmental degradation and climate change. In this light, the purpose of this study is to develop an instrument to measure product circularity, considered as an initial stage for the implementation of the circular economy. This research aims to provide the academia with a tool which, combined with other sustainability measures, would enrich the existing literature on the circular economy.

The research follows an exploratory sequential mixed methods approach to develop an instrument scale that measures the degree of circularity for technical – as opposed to biological – products, based on the parameters defined in the literature as catalysts of product circularity. The final result of the study is an instrument consisting of 32 items, representing five constructs categories: product design, business model, technological revolution, materials management, and promotion and customer involvement. The analysis of the results shows that an overall good level of validity was reached – indicating that the instrument covers all the items to reflect the definition of the circular economy.

Future research might concern further improving the validity and assessing the reliability of the proposed instrument, by performing the final of the three stages of the instrument development process – the Instrument Testing stage. Considerations on additional determinants of product circularity (e.g., the manufacturing process), on biological cycles, and on the other systemic levels of the circular economy (i.e., macro, meso and micro) should be made.

Keywords: *Circular Economy*, *Product Circularity*, *Instrument Development*

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List of Abbreviations

C2C: Cradle to Cradle

CAS: Complex Adaptive System

CEIP: Circular Economy Indicator Prototype

CET: Circular Economy Toolkit

CP: Cleaner Production

DFE: Design for Environment

DfX: Design for Sustainability

ED: Ecologically Dominant

EIP: Eco-Industrial Parks

IE: Industrial Ecology

IoT: Internet of Things

MCI: Material Circularity Indicator

NA: Non-Applicable

TBL: Triple Bottom Line

TGT: Target

1. *Introduction*

1.1 Sustainable Development and the Circular Economy

> Earth Overshoot Day marks the date when humanity's demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year. We maintain this deficit by liquidating stocks of ecological resources and accumulating waste, primarily carbon dioxide in the atmosphere (Global Footprint Network, 2019).

Over the past 40 years, Earth Overshoot Day has been occurring earlier and earlier in the year, and we are now reaching a point where 1.75 Earths are required to meet humanity's demands. *Figure 1* shows the Earth Overshoot Day trend from 1970 to 2019, and it highlights how this trend is steadily becoming a global emergency. In 2019, Earth Overshoot Day occurred on July 29th: By that date, all the regenerative resources of 2019 have been used, and we are now employing more resources than the planet can regenerate in one year (Global Footprint Network, 2019).

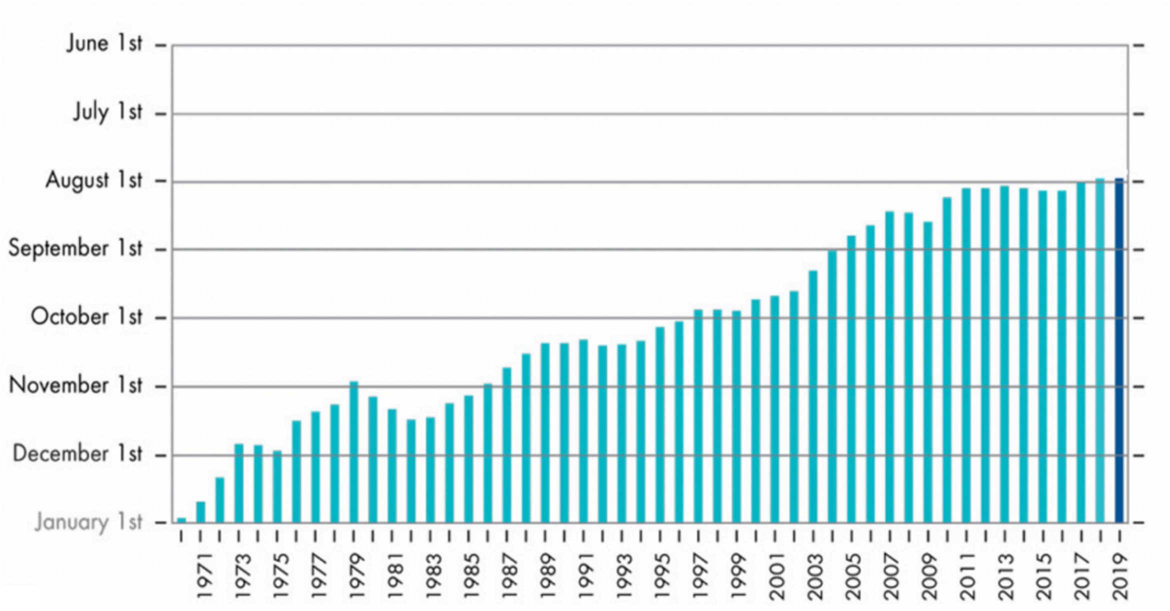

Figure 1 Earth Overshoot Day Trend. Source: Global Footprint Network (2019)

Recent decades have seen an unprecedented growth in demand for natural resources and the materials derived from them. Around 80 billion tonnes of minerals, fossil fuels, and biomass were fed into the global economy in 2011, and this is only likely to increase with population growth and improved standards of living (OECD, 2019).

To meet these global demands, today's *take-make-dispose* economy relies on the overutilization of finite resources in often-saturated markets and generates a significant amount of waste, with alarming environmental impacts (Esposito, Tse, & Soufani, 2018; Stahel, 2016) which call into question the sustainability of the current predominantly linear economic system (Ellen MacArthur Foundation, 2014).

Albeit this worrisome scenario, "the past does not necessarily determine our future" (Global Footprint Network, 2019). Through wise and forward-looking decisions, natural resource consumption trends can still be turned around, and the quality of life for all people can still be improved (Global Footprint Network, 2019). "While our planet is finite, human possibilities are not" (Global Footprint Network, 2019). The transformation to a sustainable, carbon-neutral world is both technologically possible and economically beneficial (Global Footprint Network, 2019).

In this direction, the 2030 Agenda for Sustainable Development was adopted by all United Nations Member States in 2015, providing “a shared blueprint for peace and prosperity for people and the planet, now and into the future” (United Nations, n.d.). At its core are the 17 Sustainable Development Goals, which are “an urgent call for action by all countries - developed and developing - in a global partnership” (United Nations, n.d.). They focus on strategies aimed to end poverty and other deprivations, as well as improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve oceans and forests (United Nations, n.d.).

Among the 17 Sustainable Development Goals, Sustainable Development Goal 12 is specifically concerned with responsible consumption and production to ensure sustainability within consumption and production patterns. As worldwide material consumption and material footprint per capita have expanded rapidly, urgent action is needed to avoid that the current material needs lead to the over-extraction of resources and the degradation of environmental resources. Sustainable Development Goal 12 requires the establishment of policies to improve resource efficiency, reduce waste and mainstream sustainability practices (United Nations, 2019).

In the context of sustainable development, the circular economy is emerging as a promising approach for reducing the existing global sustainability pressures, which may give rise to both economic and ecological benefits (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019). The circular economy represents a sustainable alternative to the linear industrial model and involves a systemic change of the entire operating system (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). Transforming an economic system from a linear to a circular configuration entails shifting from an industrial model based on the depletion of finite reserves to an industrial model which is restorative by intention and design (Ellen MacArthur Foundation, 2013a). The circular economy is designed on the basis of the 3R principles of reducing, reusing, and recycling, and, taking a systemic perspective, “it replaces the concept of waste with the one of restoration and aims to decouple economic growth from the use of virgin resources” (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 7).

1.2 Research Objectives and Approach

The aim of the research conducted in this thesis is to develop an instrument to measure the degree of the circular economy at the product level. The motivation for the study is that, on the one side, the increasing global sustainability pressures call for the implementation of circular industrial models as a potential solution. Therefore, it is crucial to deepen the understanding of the circular economy and its potential implications, in order to encourage its concrete application at all systemic levels (i.e., at the nano and micro level by businesses, at the meso level by supply chains and at the national level by countries). On the other side, the existing body of literature on the circular economy is still embryonic: fragmented and spread across a number of more established fields. Broadening the scope of circular economy-related research is necessary, and the objective of our thesis is, thus, to provide the academia with an effective tool which can facilitate the study of the circular economy – starting from the inner level of product circularity, to potentially develop at the other levels of implementation.

The research follows an exploratory sequential mixed methods approach – specifically, an instrument development process. The process implemented is based on Moore and Benbasat (1991)'s instrument development method, which consists of three stages: (1) Item Creation, (2) Scale Development, and (3) Instrument Testing. Of the three stages, the first two were performed in this study, in order to create an instrument scale for product circularity ensuring high levels of validity and parsimony, thus, to potentially achieve good reliability coefficients when performing the Instrument Testing.

The circular economy is conceptualized as a second order formative construct, meaning that it represents a latent variable explained by its determinants. During the Item Creation stage, these determinants were identified in the literature and defined. Five constructs were identified as catalysts or enablers of the circular economy at the product level – namely, product design, business model, technological revolution, materials management and customer involvement. Subsequently, an initial pool of 106 items was created, with the items formulated as statements regarding the five constructs on which respondents have to express their agreement on a seven-point *Likert* scale.

After the Item Creation, the Scale Development stage was conducted in order to obtain a panel of judges' opinion on the instrument and its validity. A total of sixteen judges were selected from four different areas of expertise: sustainability and/or circular economy, supply chain management, digitalization and innovation, and marketing and/or research methods. The judges were divided into four groups, and four sorting rounds were performed: in the first and third, the judges were asked to sort the items into categories identified on their own; while in the second and fourth, the judges were asked to sort the items into the five pre-defined construct categories. At the end of each round, validity considerations were made using several indicators, and, as a result, many items were dropped from the pool and many were modified. At the end of the second stage of the instrument development process, an instrument scale consisting of 32 items was created, to be tested in a pilot test with a small sample size in the third and last stage of the process.

1.3 Outline of the Thesis

The thesis is structured as follows. In *Section 2 – Conceptual Framework*, the existing literature on the circular economy is reviewed. After contextualizing the concept within the broader research area of sustainable development, the *Conceptual Framework* first provides a detailed description of the circular economy, including its principles and levels of implementations; and subsequently narrows down to the implications that the implementation of a circular industrial model would have on supply chains, and to the enablers of the circular economy at the product level.

Section 3 – Theoretical Framework represents the theoretical foundation within which the circular economy is researched throughout this study. The chapter describes two main and contrasting theories of the supply chain, and follows with a discussion on the challenges of developing a circular industrial model within such theoretical background, thus on the relevance of the research hereto conducted – aimed to provide the academia with an instrument to further research the circular economy, thus to broaden the existing theory on the concept.

Section 4 – Research Scope and Literature Review is divided into two main sections: The first outlines the problem formulation to conclude with the statement and description of the research question addressed in the study. The latter represents a review of the existing instruments to measure the circular economy, focused on an analysis of their strengths and weaknesses.

In *Section 5 – Research Design and Methodology*, the type of study conducted is described, first from a research design perspective, thus focusing on the exploratory sequential mixed methods design adopted, followed by a detailed description of the instrument development process implemented, of which two out of the three existing stages were performed in this study.

Lastly, *Section 6 – Results and Discussion* provides an analysis and discussion of the results. The chapter is followed by a conclusion on the insights gathered from the conducted research and on the perspectives on future research.

2. *Conceptual Framework*

2.1 Sustainable Development

The relationship between businesses and the environment has gained much interest recently, questioning the sustainability of the current economic system, due to the increasing degradation of the planet's ecosystems, to climate change, and to water, air and soil pollution. On their side, businesses are failing to address the concerns which are related to sustainability, overusing natural resources, not responding to global warming and not focusing on social justice (Murray, Skene, & Haynes, 2017). Therefore, in order to define businesses' responsibility towards the environment and the society, the notion of sustainable development has become of particular relevance (Burgos Jiménez & Céspedes Lorente, 2001).

According to the report "*Our common future*" by the World Commission on Environment and Development (1987), sustainable development is the one which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 42). Nowadays, businesses are using resources that are not renewable and they are using more than what they might actually replace. On top of this, the threat of climate change makes it necessary for companies to design business models which entail more sustainable ways of living, manufacturing and consuming.

From a corporate point of view, this definition requires firms to fit their organisational systems into broader social and ecological systems. As a matter of fact, even if sustainable development must come from businesses, governments and consumers together, firms play a crucial role in slowing down the planet's deterioration. This responsibility comes from the amount of financial resources, technological knowledge and institutional capability they possess, which must converge into finding solutions for environmental problems. Furthermore, the development of environmental solutions entails for firms, most of the time, competitive advantage (Burgos Jiménez & Céspedes Lorente, 2001).

Firms might contribute to sustainable development by innovating products and processes in order to use raw materials more efficiently, improving at the same time corporate and product image, being more environmentally responsible while improving working conditions. All of these factors might ultimately achieve economic, environmental and social goals (Burgos Jiménez & Céspedes Lorente, 2001). In this way, the so-called *win-win-win strategies* defined by Elkington (1994, p. 90), which simultaneously benefit the company, the customers and the environment at the same time, have arisen. They entail an improvement in environmental performance, customer satisfaction and company performance (Burgos Jiménez & Céspedes Lorente, 2001). Businesspeople must be actively involved, and they must be conscious that they play a crucial role in achieving the aim of sustainable development strategies (Elkington, 1994).

One of the determinant concepts in the sustainability research is the Triple Bottom Line (TBL). This terminology has been credited to Elkington (1994). The TBL is defined as an accounting framework, which goes "beyond the traditional measures of profits, return on investment, and shareholder value to include environmental and social dimensions" (Slaper & Hall, 2011, p. 1) and where the three aspects (economic, environmental and social) are treated with equal importance. The three performance dimensions that it incorporates – social, environmental and financial – are also commonly called three Ps, i.e., people, planet and profits. The literature provides a measure for the TBL, to assess how much one firm's activities impact its profitability, values to shareholders, and its social, human and environmental capital. In raising awareness for more sustainable products, crucial determinants are, on the one side, the public opinion and, on the other, the business-to-business pressure and the development and implementation of systematic review of suppliers. Indeed, one of the main findings in the literature was that many environmental problems were being imported throughout the supply chain (Müller & Seuring, 2008). Müller and Seuring (2008) define the supply chain and supply chain management as:

> All activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows. Material and information flow both up and down the supply chain. Supply chain management (SCM) is the integration of these activities through improved supply chain relationships to achieve a sustainable competitive advantage (Müller & Seuring, 2008, p. 1700).

Indeed, the focal company, i.e., the one that usually rules the supply chain and that designs the products offered, is directly linked to the customers, may be held responsible for the environmental and social performance of its suppliers (Müller & Seuring, 2008). Sustainable supply chain management is defined more widely as:

> The management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements (Müller & Seuring, 2008, p. 1700).

One of the main duties of a business should be to evaluate its suppliers and exclude from its supply chain the ones which perform worse in terms of environmental impacts, e.g., air and water pollution, land releases, consumption and sources of energy (Elkington, 1994).

Sustainable products are all those kinds of products that have or aim to improve environmental and social quality, mainly implementing environmental and social standards. However, their ultimate goal is gaining customer satisfaction and competitive advantage in the market. In this regard, sustainable supply chain management must account for the lifecycle management, i.e., the focal company becomes in charge of demanding to its suppliers a green supply chain. In line with this, the need for cooperation and deep information flows among suppliers increases at all levels and among a wider range of companies. Indeed, environmental and social criteria must be applied not only to final products but throughout all the supply chain by means of environmental and social standards (Müller & Seuring, 2008).

Furthermore, according to Montabon, Pagell and Wu (2016), along their supply chain, businesses should apply the so-defined Ecologically Dominant (ED) logic as opposed to the Instrumental Logic or TBL (Montabon, Pagell, & Wu, 2016). Specifically, the fact that companies have to offset their supply chain's negative impact on the environment and society, does not entail that such supply chain is definable truly sustainable. On the contrary, firms should apply an ED logic, able to lead to true sustainable supply chains, where the environmental and social interests replace the economic ones. In other words, firms must ask themselves how to develop a sustainable supply chain, rather than how to address environmental and social issues can benefit their supply chain (Montabon, Pagell, & Wu, 2016).

While the Instrumental Logic entails that the main goal of the firm lies in its economic performance – reducing the harm it causes to the environment while maintaining or even increasing its profits – the ED logic prioritises the future society at large rather than individual firms and existing supply chains. The TBL dimensions are nested; firstly, firms must account for the environmental interests, then the social and only finally the economic ones. It entails a long-term perspective where the main goal is not doing harm and then satisfying customers' needs (Montabon, Pagell, & Wu, 2016).

2.2 The Circular Economy

2.2.1 Sustainability and the Circular Economy

In the setting of sustainable development, there is a need for a "holistic approach to be taken by societies (including businesses) toward issues of consumption in general" (Murray, Skene, & Haynes, 2017, p. 370). In order to address the ecological questions and environmental challenges that gained increasing relevance in recent years, the circular economy is emerging as a possible solution companies can adopt (Murray, Skene, & Haynes, 2017). Indeed, the concept of circular economy is regarded as an alternative which may give rise to both economic and ecological benefits (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019).

Although the concept of circular economy is increasing its presence in the academic debates on sustainability, there is not a general consensus on the theoretical framework of the circular economy; however, many authors agree that the circular economy lays within sustainable development (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019). More specifically, Suavé, Sloan and Bernard (2016) conclude that most authors presented sustainable development and the circular economy as coherent, and even interdependent, disciplines; precisely, "circular economy becomes a tool for sustainable development" (Suavé, Sloan, & Bernard, 2016, p. 54). As a matter of fact, the circular economy is viewed as an operationalisation for businesses, in order to implement the concept of sustainable development

(Ghisellini, Cialani, & Ulgiati, 2016; Murray, Skene, & Haynes, 2017; Kirchherr, Reike, & Hekkert, 2017).

In the literature, the relationship between sustainable development and the circular economy was identified in three different possible connections: 1) the circular economy is necessary for sustainable development; 2) the circular economy is beneficial to sustainable development; and 3) the circular economy and sustainable development have a compensatory relationship. Suárez-Eiroa, Fernandez, Méndez-Martínez and Soto-Oñate (2019), therefore, conclude that: *i*) there is a close relationship between both sustainable development and the circular economy and *ii*) the circular economy is at least beneficial to achieve sustainable development. In other words, sustainable development establishes goals to be achieved in order to solve the problems and their consequences, whereas the circular economy is a tool to address some of the causes of these problems (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019, p. 955).

By contrast, other authors believe that the circular economy misses out the social aspect of sustainable development, considering only its economic and environmental goals (Suavé, Sloan, & Bernard, 2016; Murray, Skene, & Haynes, 2017). Indeed, in the provided definition of sustainable development and in the three pillars of sustainability (i.e., economic, environmental and social) there is a direct emphasis on the concept of stakeholders' well-being and human rights. Thus, sustainable development promotes some forms of both inter-generational equity among the people of the present and the one who will live the planet in the future, and intra-generational equity among the ones currently populating the planet, including equity and social justice as fundamental aspects within sustainability (Murray, Skene, & Haynes, 2017). Most authors agree that the circular economy is comprehensive of the economic and ecological dimensions of sustainable development, but that it misses out the social component (Suavé, Sloan, & Bernard, 2016; Murray, Skene, & Haynes, 2017; Kirchherr, Reike, & Hekkert, 2017). As a matter of fact, the circular economy seems more focused on the redesign of (manufacturing and service) systems, in order to benefit the planet in terms of ecological renewal and survival and reduction in the use of finite resources (Murray, Skene, & Haynes, 2017). However, according to Suárez-Eiroa, Fernandez, Méndez-Martínez and Soto-Oñate (2019), since the circular economy is a tool to reach targets of sustainable development, "a transference of a certain responsibility of social targets to the circular economy is inevitable and the achievement of social goals results inherent to the consecution of ecological and economical aims" (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019, p. 957).

Consequently, the circular economy might be placed between the ecological, economic and social dimensions of sustainability. Specifically, the aim of the circular economy under the sustainable development framework should be to "decouple economic development from the utilization of finite resources and wastes and emissions generation, by maintaining extraction rates of resources and generation rates of wastes and emissions under suitable values for planetary boundaries" (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019, p. 957).

In conclusion, the circular economy concept is compatible and consistent with sustainable development and its three pillars. Indeed, "it aims directly not only at economic benefits (e.g., value creation and savings by reducing the purchase of primary raw materials), but also at environmental benefits (e.g., impact reduction) and indirectly at social benefit (e.g., job creation)" (Saidani, Yannou, Leroy, & Cluzel, 2017, pp. 1-2).

2.2.2 Definitions of the Circular Economy

Although the concept of circular economy is gaining increasing momentum among academics and business practitioners, in the literature there is still not a commonly accepted definition and it is argued that there are various possibilities when defining the circular economy. An important work in this regard is the one presented by Kirchherr, Reike and Hekkert (2017) who collected 114 definitions of the circular economy in order to understand their common dimensions. The result of their research suggests that the circular economy is frequently described as a combination of reduce, reuse, and recycle activities.

Murray, Skene and Haynes (2017) stated that the origin of the term can be traced back to Boulding (1966) who reported that "man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy" and highlighted the importance of durability and of the closed-up economy (Boulding, 1966, pp. 7-8). The meaning of the term *circular economy*, according to Murray, Skene and Haynes (2017), is twofold: on the one side, from a linguistic perspective it is the antonym of *linear economy* while, on the other side, it includes a descriptive meaning.

First, all circular economy definitions agree that the circular economy is to be considered as opposed to the linear model *take-make-dispose* according to which "companies extract materials, apply energy to them to manufacture a product, and sell the product to an end consumer, who then discards it when it no longer works or no longer serves the user's purpose" (Ellen MacArthur Foundation, 2013a, p. 15). According to Cooper (1999):

> The model of a linear economy, in which it is assumed that there is an unlimited supply of natural resources and that the environment has an unlimited capacity to absorb waste and pollution, is dismissed. Instead, a circular economy is proposed, in which the throughput of energy and raw materials is reduced (Copper T. , 1999, p. 10).

Indeed, in principle, the circular economy "restores any damage done in resource acquisition, while ensuring little waste is generated throughout the production process and in the life history of the product" (Murray, Skene, & Haynes, 2017, p. 371).

Second, the meaning of the circular economy is descriptive and related to the concept of *cycle:* "circular economy is looking for a better management of resources throughout the lifecycle of systems and it is characterized by closed loops, promoting maintenance, reuse, remanufacturing and recycling" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 3). Biogeochemical cycles and the idea of recycling become of particular relevance. On the one hand, it is argued that all the biogeochemical cycles have been altered by human activities. Thus, the circular economy aims to both slow down and manage fluxes, in order to restore them to their natural levels, "reducing the excessive removal of material from a cycle, and the excessive release of materials into a cycle" (Murray, Skene, & Haynes, 2017, p. 371). On the other hand, the circular economy is strictly connected to the idea of resource cycling. In other words, in the circular economy, each company uses the waste of others as a resource. Firms must put their effort in order to slow down the cycle of use of their products and to delay for as long as possible the waste output. In order to increase the longevity of products, each firm must decrease its rate of replacement, improving its manufacturing and maintenance, and therefore reducing the use of resources. In this setting, two concepts emerge: one is linked to the definition presented above of the 3R, i.e., the Reduce, Reuse and Recycle framework; the other one is related to the expression *waste-is-food* (Simmonds, 1862) which entails how "unwanted outputs of one industrial process are used as raw materials in another industrial process" (Murray, Skene, & Haynes, 2017, p. 371).

The most employed definition of the circular economy is the one provided by the Ellen MacArthur Foundation (2013a):

> 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, 2013a, p. 7).

Overall, the circular economy is related to the sustainable environment to the extent that it covers all those activities that "reduce, reuse, and recycle materials in production, distribution, and consumption processes based on ecological circulation of natural materials" (Murray, Skene, & Haynes, 2017, p. 373). Moreover, the implementation of the circular economy must occur at three system levels: macro-system, e.g., city province, region, nation level; meso-system, e.g., eco industrial parks level; micro-system, e.g., products, individual enterprises and consumers (Ghisellini, Cialani, & Ulgiati, 2016). A broader overview of the most common definitions of the circular economy provided by the literature is summarised in *Table 1*, retrieved from the research of Kirchherr, Reike and Hekkert (2017) and Suárez-Eiroa, Fernandez, Méndez-Martínez and Soto-Oñate (2019).

Circular Economy systems keep the added value in products for as long as possible and eliminates waste. They keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value (European Commission, 2015; European Commission, 2014a).
The Circular Economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It enables key policy objectives such as generating economic growth, creating jobs, and reducing environmental impacts, including carbon emissions (Ellen MacArthur Foundation, 2015).
Model of production and consumption of goods through closed loop material flows that internalize environmental externalities linked to virgin resource extraction and the generation of waste (including pollution) (Suavé, Sloan, & Bernard, 2016).

We define the Circular Economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).
The Circular Economy is an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being (Murray, Skene, & Haynes, 2017).
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 operational 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 (Kirchherr, Reike, & Hekkert, 2017).
The Circular Economy is a sustainable development initiative with the objective of reducing the societal production-consumption systems' linear material and energy throughput flows by applying materials cycles, renewable and cascade-type energy flows to the linear system. Circular economy promotes high value material cycles alongside more traditional recycling and develops systems approaches to the cooperation of producers, consumers and other societal actors in sustainable development work (Korhonen, Nuur, Feldmann, & Birkie, 2018).
The Circular Economy is a regenerative production consumption system that aims to maintain extraction rates of resources and generation rates of wastes and emissions under suitable values for planetary boundaries, through closing the system, reducing its size and maintaining the resource's value as long as possible within the system, mainly leaning on design and education, and with capacity to be implemented at any scale (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019).

Table 1 Explicit definitions of Circular Economy. Source: Suárez-Eiroa, Fernandez, Méndez-Martínez, and Soto-Oñate (2019, p. 955)

2.2.3 The Circular Economy Principles

According to Ghisellini, Cialani and Ulgiati (2016), and confirmed by the study on 114 circular economy definitions by Kirchherr, Reike and Hekkert (2017), the circular economy is founded on three key principles, i.e., the 3Rs: Reduce, Reuse and Recycle. The Reduce principle concerns the minimisation of input of primary energy, raw materials and waste through the improvement in the efficiency of the production and consumption processes. In this setting, the concept of *resource efficiency* emerges, which implies the simultaneous reduction of the amount of resources deployed and the amelioration of economic and social well-being (Ghisellini, Cialani, & Ulgiati, 2016). The Reuse principle consists of "using again a product or a component which is not waste for the same purpose for which it was conceived" (Ghisellini, Cialani, & Ulgiati, 2016, p. 15). In so doing, the reuse of products requires fewer resources compared with the manufacture of new products from virgin materials, leading, overall, to environmental benefits (Ghisellini, Cialani, & Ulgiati, 2016). The Recycle principle refers to:

> Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations (Ghisellini, Cialani, & Ulgiati, 2016, p. 16).

Recycling waste means "benefitting from still usable resources and reducing the quantity of waste that need to be treated and or/disposed of", therefore decreasing the related environmental impact (Ghisellini, Cialani, & Ulgiati, 2016, p. 16).

Despite the fact that the circular economy is often identified with the recycling principle (Kirchherr, Reike, & Hekkert, 2017), recycling might actually be the least sustainable option with respect to the other circular economy principles in terms of resource efficiency and profitability; indeed, recycling "is limited by nature (entropy law), material complexity and abuse" (Ghisellini, Cialani, & Ulgiati, 2016, p. 16); moreover, some waste materials are by their nature unrecyclable and others, even if recyclable, might be recycled only up to a certain point, after which they inevitably become waste (Ghisellini, Cialani, & Ulgiati, 2016). The 3R principles are combined with the circular economy principles developed by the Ellen MacArthur Foundation (2013a), presented in detail in *Section 2.3*.

2.2.4 The Antecedents of the Circular Economy

The concept of circular economy finds its antecedents in broader historical, economic, and ecological fields (Murray, Skene, & Haynes, 2017). Specifically, the concept of circular economy cannot be traced back to a single author; indeed, several schools of thought put the basis for the development of the concept, namely: Regenerative Design, Performance Economy, Cradle to Cradle, Industrial Ecology, and Biomimicry (Ellen MacArthur Foundation, 2013a).

Regenerative Design

Regenerative Design comes from the thought of Lyle, American professor who launched the challenge of carrying out daily activities purely living within the limits of available renewable resources and without generating environmental degradation. Indeed, the term regenerative design highlights that systems should follow a regenerative path, meaning that "processes themselves renew or regenerate the sources of energy and materials that they consume" (Ellen MacArthur Foundation, 2013a, p. 26).

Performance Economy

The school of thought of Performance Economy might be traced back to Stahel, who gave its contribution to the research report of the European Commission *The Potential for Substituting Manpower for Energy*, supporting the vision of an economy in loops (or circular economy) and its impact on job creation, economic competitiveness, resource savings, and waste prevention (Ellen MacArthur Foundation, 2013a). Stahel's way of thinking is believed to be crucial in putting the basis of the circular economy, particularly regarding its four main goals: "product-life extension, long-life goods, reconditioning activities, and waste prevention" (Ellen MacArthur Foundation, 2013a, p. 26). The importance of the *functional service economy* is also underlined, which sells services rather than products, and can be more widely included in the idea of *Performance Economy*. Finally, it is argued that the circular economy should be a valuable response to the end of the era of low-cost oil and materials (Ellen MacArthur Foundation, 2013a).

Cradle to Cradle

Starting from Lyle's Regenerative Design, McDonough and Braungart (2002) are the developers of the Cradle to Cradle (C2C) ® concept and certification process. The term is used as opposed to the Cradle to Grave model which, "generates product designed for a one way trip to the landfill"; on the contrary, the C2C design is defined as "the foundation for a transition from products designed for a one-way trip to the landfill to industrial systems that restore nature, eliminate the concept of waste, and create enduring wealth and social value – human industry as a regenerative force" (McDonough & Braungart, 2002, p. 255). Indeed, C2C is a design philosophy to systems development which promotes the adaptation of nature to industrial models. In other words, it considers that all the materials involved in industrial and commercial processes are nutrients (which might be either technical or biological), which ultimately must regenerate. Specifically, technical nutrients are "non-toxic, non-harmful synthetic materials" which might be continuously used preserving their integrity and quality, staying in a continuous cycle. In this way, they are not downcycled, i.e., used into lesser products, eventually becoming waste. Biological nutrients, on the other hand, are organic materials that, after their use, can be disposed of in any natural environment since they decompose into the soil, water, etc., without generating any negative effect to the environment, rather providing food in the ecosystem. The main principle of the C2C design is that industries, in their production processes, must preserve and enrich ecosystems and the biological cycles of nature, maintaining, at the same time, an efficient and high-quality use of both technical and biological nutrients. As a matter of fact, this holistic vision includes both the industrial, social and economic dimensions, aiming at creating systems which are not only efficient, but environmentally compatible and waste free. However, in order to apply the *biological metabolism* into the *technical metabolism*, i.e., developing quality-based recycling systems, it is essential to precisely define the molecular composition of materials and reporting the presence of any particular hazardous material. Other than material health*,* other certification criteria for the C2C products are material reutilisation, energy assessment, water usage and social responsibility. Indeed, the C2C framework assesses not only materials but also energy and water input and it is strictly connected to the three key principles: "1) Waste equals food, 2) Use current solar income, 3) Celebrate diversity" (Ellen MacArthur Foundation, 2013a, p. 28). Moreover, the C2C model is not only applicable in the industrial and manufacturing context, rather it might be applied also to urban environments, buildings, and economic and social systems.

Industrial Ecology

Industrial Ecology (IE) is the study of materials and energy flows through industrial systems. It argues that industrial systems might be viewed to a certain extent as ecosystems. Precisely, industrial systems, as well as natural ecosystems, might be defined as a particular distribution of materials, energy, and information flows. Besides, the whole industrial system depends on the resources and services supplied by the biosphere (Erkman, 1997). The IE goes further the notion of industrial metabolism. While industrial metabolism is "the whole of materials and energy flows going through the industrial system", the core of the IE is to:

> Understand how the industrial system works, how it is regulated, and its interaction with the biosphere; then, on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function (Erkman, 1997, p. 1).

Specifically, the IE refers to the shifting of industrial processes from linear to circular systems. Conversely to linear – or open loop – models, where resources enter the system as input and leave the system becoming waste, the IE aims to develop closed-loop processes where waste becomes input for new processes. Besides, the IE is partitioned in three levels: single enterprise, inter-firm clusters at the supply chain level, and cities/municipalities. The IE focuses on the importance of action not only at the component level and improvement of resource utilisation, rather on an optimisation through a redesign of all the industrial systems. The IE is characterised by three key principles: 1) it adopts a systemic, comprehensive, integrated approach of all the components of the industrial economy and their relations with the biosphere; 2) it emphasises the biophysical foundation of human activities, i.e., the economy cannot be considered in terms of absolute money units, rather as a flow of materials and energy within and outside the industrial system; 3) it includes technological dynamics, i.e., technological development is considered as a crucial element for the shift from an unsustainable industrial system to an industrial ecosystem (Erkman, 1997). Moreover, the IE adopts a lifecycle thinking, which implies the necessity to account for all the environmental effects related to a component, product or system during its lifecycle. This is crucial to avoid transferring environmental impacts from one lifecycle phase to another, e.g., re-designing a product in order to deploy less resources, yet more difficult to be disposed of; clearly, this re-design entails an actual shifting of the product's environmental impacts from the extraction to disposal phase. Lastly, the IE framework has a multidisciplinary and interdisciplinary approach which entails that it might be referred to as the "science of sustainability" (Ellen MacArthur Foundation, 2013a, p. 27). As a matter of fact, the IE considers three different disciplines: social, technical and environmental sciences. Therefore, given its focus on natural capital renewal as well as social wellbeing, it might also be applied in the services sector (Ellen MacArthur Foundation, 2013a).

Biomimicry

The term biomimicry is traced back to the book *Biomimicry: Innovation Inspired by Nature* (Benyus, 2002) and it is defined as a "new science that studies nature's best ideas and then imitates these designs and processes to provide innovative and sustainable solutions for industry and research and to solve human problems". In other words, "it is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies" (Biomimicry Institute, n.d.). The book *Innovation Inspired by Nature* reports the three key principles biomimicry relies on: treating nature as (1) a model, (2) a measure and (3) a mentor. The principle of nature as a model highlights the importance of studying the models found in nature and emulating their forms, processes, systems, and strategies to solve human problems. Nature as a measure recalls the use of ecological standard to judge the sustainability of innovation. Finally, nature as a mentor suggests valuing nature not as something to be exploited, rather according to what it might be learnt from it. There are nine basic laws at the basis of the concept of biomimicry, i.e., nature runs on sunlight, nature uses only the energy it needs, nature fits form to function, nature recycles everything, nature rewards cooperation, nature banks on diversity, nature demands local expertise, nature curbs excesses from within, nature taps the power of limits which should be translated to create alternative sustainable technologies (Benyus, 2002).

2.2.5 Implementation Levels of the Circular Economy

In the literature, there is a widespread consensus about the existence of three implementation levels of the circular economy: macro level, meso level and micro level (Ghisellini, Cialani, & Ulgiati, 2016; Kirchherr, Reike, & Hekkert, 2017; Murray, Skene, & Haynes, 2017). The macro level refers to the implementation of circular economy systems in the whole society, at the cities, regions, nations and international community levels, "adjusting the industrial composition and the structure of the entire economy" (Kirchherr, Reike, & Hekkert, 2017, p. 224). The meso, or regional, level refers to the inter-firm implementation of the circular economy, with a focus on eco-industrials parks as systems. The micro level refers to the implementation of the circular economy at the company level (Suárez-Eiroa, Fernandez, Méndez-Martínez, & Soto-Oñate, 2019). Kirchherr, Reike and Hekkert (2017) include in the micro-system perspective customers as well as what is needed to increase product circularity. On the other hand, Saidani, Yannou, Leroy, and Cluzel (2017) and the World Business Council for Sustainable Development (2018) identified a fourth lower implementation level: the nano level. The nano level refers to the implementation of the circular economy in products and components; in other words, it is:

> An operational and product-level including components and materials, which could serve as a common denominator within the three levels, and could enable not only to make the links between these levels but also to have a closer look at the effective performance of circular economy implementation (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 5).

Macro Level

The implementation of the circular economy in cities, provinces and regions requires the redesign of four systems: the industrial system ("changing the size of companies from small to large or the phase-out of the heavy polluting enterprises in favour of light economic activities as related to high-tech industries, tourism or culture"), the infrastructure system ("transportation and communication systems, water-recycling systems, clean energy and electrical power lines, etc.") and the cultural and social system (Ghisellini, Cialani, & Ulgiati, 2016, p. 22). For instance, some cities in the USA and Japan were redesigned into eco-cities in line with ecological principles, achieving both zero emissions goals and economic benefits. Japan counts 26 successful eco-towns. Other eco-cities might be found in Europe (in Germany, Sweden, and the United Kingdom) as well as in China. They mostly gain from an efficient use of resources, and a reduction in energy and water consumption. In this setting, however, it is critical that governments intervene in order to introduce regulations and promote waste management programmes or, in some cases, to finance innovative ecological projects (Ghisellini, Cialani, & Ulgiati, 2016).

On the consumers side, collaborative consumption models, e.g., sharing, bartering, lending, trading, renting, gifting, are some of the possible options which lead consumers to shift towards implementing the circular economy. The main principle of collaborative consumption models consists in giving up the ownership of the product; in other words, these business models are based on selling services rather than selling products. The consequent loss of ownership, however, might be one of the biggest barriers to the development of such systems. Moreover, for these systems to work, consumers must be part of a larger network (e.g., big cities) where they might easily have access to such schemes (Ghisellini, Cialani, & Ulgiati, 2016).

It is also essential for cities and regions to have innovative waste management and zero-waste programmes in place. For instance, it is argued that through prevention, recycling and recovery of waste, it is possible to critically reduce environmental impacts compared to disposing waste in the landfill. Ideally, the circular economy would aim to pull all waste down to zero. Although it is not possible to recycle all kinds of material, the European Union included the zero-waste goal in the 7th Environment Action Program, with the objective of: "virtually eliminating landfilling by 2020". Some Member States (Austria, Belgium, Denmark, Germany and the Netherlands) have already achieved the objectives included in the EU Landfill Directive, putting strong efforts towards the elimination of landfilling and the increase of recycling rates (Ghisellini, Cialani, & Ulgiati, 2016, p. 24). It is worth noticing that the shift towards low landfill rates creates down-side-effects regarding the final dismissing of the remaining landfills. For this reason, it is essential for local authorities to preventively plan their capacity to prevent waste disposal abroad (Ghisellini, Cialani, & Ulgiati, 2016).

Meso Level

At the meso level, the implementation of the circular economy entails the development of eco-industrial parks (EIPs), industrial symbiosis districts and networks. Within industrial symbiosis, industries do not act as separate entities, but rather as a network of resource exchange, with the goal of benefitting both the economy and the environment. Indeed, industrial symbiosis entails the exchange of by-products and sharing of resources among several independent organisations as long as waste, emissions and energy demand, factors which depend on the distance among participants, do not outweigh the benefits (Ghisellini, Cialani, & Ulgiati, 2016).

While industrial symbiosis is a bottom up strategy, i.e., participant companies spontaneously agree on it, EIPs have a top down approach, i.e., they are preventively planned and designed.

Many EIPs can be found in the United States, Canada, India, Korea, Japan, Australia, Brazil, Egypt and Europe. Worth noticing are the EIPs of Kalundborg in Denmark and Styria in Austria. The former started as industrial symbiosis among five companies and eventually turned in a bottom up eco-industrial park; while, in the latter, participants started recognising environmental benefits after some time.

The economic benefits are both direct, e.g., "revenues from selling by-products, reduced costs from avoided discharge fees or disposal costs, reduced costs deriving from substituting virgin energy and materials with alternative feedstock obtained at lower prices" and indirect, e.g., "avoidance of investments, increase of supply security and flexibility, better reputation, innovation, operational resiliency, and ability to attract and retain employees". However, recently, it is argued that eco-industrial parks and industrial symbiosis are less focused on "physical exchanges of materials, energy, water and by-products in favour of sharing more about infrastructure and knowledge, joint sourcing, building local supply chain and reducing the risks from weather and other business disruptions" (Ghisellini, Cialani, & Ulgiati, 2016, p. 20).

In China, the Chinese State Environmental Protection Administration has started to promote industrial symbiosis and EIPs since the 90s', trying to develop a unique EIP model, in order to bounder the issue of highly polluted industrial development zones. In addition to the traditional industrial parks' features, the EIPs are seen as a new type of industrial parks which involve a network of different industries in "by-products exchange, water and energy cascading, and information sharing", aiming at "the creation of closed loops, the minimization of waste and overall eco-efficiency improvements by applying the principles of cleaner production, industrial ecology and circular economy" (Ghisellini, Cialani, & Ulgiati, 2016, p. 21). From 2001 to 2011, China developed the largest national EIP network consisting of 60 National Trial EIPs. In the largest industrial park, an integrated solid waste management was applied, aimed at maximising resource use and minimising the waste produced and the costs of disposal. In order to do so, cleaner production programmes were introduced at the company level as well as the employment of new scavengers and decomposers at the inter-firm level (Geng, Zhu, & Haight, 2007). The benefits of EIPs are multiple: economic, e.g., "costs savings in resource use, increase of revenues from the sale of waste"; environmental, e.g., "ease of virgin materials exploitation and reduction of waste quantity as well as decrease of waste amount disposal to landfill"; and social, e.g., "improved public health by reducing solid and hazardous waste, employment opportunities for local scavengers and decomposers companies, etc." (Ghisellini, Cialani, & Ulgiati, 2016, p. 21). However, it is argued that businesses mainly establish industrial symbiosis to gain economic benefits rather than environmental and social ones, e.g., "recovering of the costs in environmental investments, cost saving from virgin material substitution and transport, business visibility and social identity, social responsibility of enterprises" (Yu, Han, & Zhaojie, 2015).

Micro Level

At the micro level, the implementation of the circular economy occurs in three sectors: the production sector, the consumption sector and the waste management sector (Ghisellini, Cialani, & Ulgiati, 2016). Preparatory stages towards the adoption of circular economy programmes in production processes are eco-design or green design, design for environment (DFE) and cleaner production (CP) strategies.

Both DFE and eco-design "blend environmental aspects into product design and development at product conception to enhance environmental performance throughout its lifecycle" (Ghisellini, Cialani, & Ulgiati, 2016, p. 18). Precisely, eco-design aims at creating environmentally friendly products and processes, meanwhile assuring high quality standards and product's functionality and safety. Eco-design implies that the design stage of products acquires particular relevance when assessing products' relative sustainability; in other words, it becomes crucial to consider all the environmental impacts of a product starting from the earliest stage of design. Eco-design prevents uncoordinated product planning; for instance, shifting negative impacts from one stage of the lifecycle to another, e.g., eliminating a toxic substance from a product should not turn in higher energy consumption, which might ultimately impact negatively the environment (European Commission, 2014a). Therefore, "disassembly, disposability without negative environmental impacts, ease of distribution and return, durability, reliability and customer success" should be considered as relevant aspects towards the implementation of the circular economy (Ghisellini, Cialani, & Ulgiati, 2016, p. 18). A concrete example of eco-design implementation is the Eco-Design directive adopted by the European Union in 2005 which "provides a coherent and integrated framework which allows setting mandatory eco-design requirements for some products". In 2009, the Eco-Design directive was extended to include not only energy-using products but also all other energy-related products whose use impacts directly or indirectly energy consumption. The requirements of the Eco-Design directive concern, for instance, setting limit values, such as maximum energy consumption or minimum quantities of recycled material. However, EU directives are not binding, products requirements must be set in Commission Regulations (European Commission, 2014a).

Besides eco-design, CP is also considered a crucial strategy towards the circular economy and sustainable development. Specifically, it aims at diminishing waste and emission flows and at reducing the use of non-renewable resources by introducing cleaner products, processes and services in order to enhance the overall economic efficiency and prevent damages and risks for humans and the environment (Ghisellini, Cialani, & Ulgiati, 2016). For instance, China has promoted the CP with the adoption of the Cleaner Production Promotion Law in 2002, in order to improve energy conservation; moreover, many Chinese enterprises are investing in project regarding CP technologies (Ghisellini, Cialani, & Ulgiati, 2016).

Concerning the consumption sector, consumers' responsibility and green public procurement are essential aspects towards the circular economy. Indeed, it is crucial to promote consumers' responsibility in order to increase the purchase and use of sustainable goods. For instance, information and labelling systems are gaining increasing relevance among countries. In the European Union, the EU Ecolabel, established in 1992 and recognised worldwide, identifies products which meet the high environmental standards created by a panel of experts, consumer organisations and industry based on the environmental impacts of the product throughout its lifecycle (European Commission, n.d. a). On the other hand, since public procurement accounts for a significant portion of countries' gross domestic product, the green public procurement becomes a critical policy tool to contribute to sustainable consumption (European Commission, n.d. b). The green public procurement might indeed be translated into "setting and including "green" requirements before awarding public contracts" (Ghisellini, Cialani, & Ulgiati, 2016, p. 19). Although the implementation of green public procurement plans is increasing (China, Japan, Taiwan, Korea, Malaysia and the United States have already green public procurement schemes in place), its development is not yet satisfactory. Moreover, the green public procurement would require clear and verifiable environmental criteria for products and services in the public procurement process (European Commission, n.d. b).

Lastly, waste management plays a crucial role in the implementation of the circular economy. Generally, waste management refers to the disposal of waste materials by landfill or incineration which, in so doing, generates a huge loss of valuable resources and harmful effects on the environment. In the circular economy setting, waste management changes its connotation and it becomes a recovery of resources and environmental impact prevention. Specifically, new operators and processes collect waste and transform or recycle waste resources by applying innovative technologies (Ghisellini, Cialani, & Ulgiati, 2016).

2.3 The Circular Supply Chain

2.3.1 The Limits of the Linear Supply Chain

As described in *Section 2.2*, the circular economy is normally conceptualized at four distinct systemic levels: macro, meso, micro and nano. For the purpose of this study, the present research is conducted at the nano level and from the perspective of the focal firm in the context of its supply chain. The rationale for conducting the research at the supply chain level stems from the acknowledgment that the main sustainability challenges firms are facing emerge in the supply chain (Jungmichel, Schampel, & Weiss, 2017). As a matter of fact, in the attempt of creating a sustainable production system, the step of "taking a holistic view of the whole product supply chain" is crucial (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017, p. 443).

The majority of supply chains are currently designed on a linear industrial model, based on the *take-make-dispose* paradigm. In a linear supply chain, "virgin materials are taken from nature, used to make products, which are then used and eventually disposed of" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 7). Once a product is sold, ownership and liability for risks and waste pass to the buyer, who arbitrarily decides whether to reuse, recycle, or dump the product at the end of its lifecycle (Stahel, 2016).

If this linear economy model of mass production and mass consumption guarantees a desirable outcome due to the creation of wealth resulting from the economic activity and the trade of goods and services (Genovese, Acquaye, Figueroaa, & Koh, 2017), it has also become undeniable that the overutilization of resources in often saturated markets and the significant amount of waste generated have unsustainable environmental impacts (Esposito, Tse, & Soufani, 2018; Stahel, 2016). More specifically, on one hand the increasing pressures on global resources and climate change caused by human activity are causing worsening ecological trends, and on the other hand the high and volatile prices of limited natural resources are threatening the competitiveness among countries and increasing companies' risk exposures (Di

Maio & Rem, 2015; Bocken, De Pauw, Bakker, & Van Der Grinten, 2016; Ellen MacArthur Foundation, 2013b).

The environmental consequences of the current *take-make-dispose* system include toxic waste, water pollution, loss of biodiversity, deforestation, long-term damage to ecosystems, hazardous air emissions, greenhouse gas emissions and energy use (DIEH; COWI, SMEdenmark, 2010), and entail significant resource losses, waste within the production chain and at the end of a product's lifecycle, significant energy waste, and the erosion of ecosystem services (Ellen MacArthur Foundation, 2013a). The food, automotive, chemical, paper and fashion industries are based on the most damaging production systems. Large industries, as the automotive and chemical, cause the largest *absolute* environmental impact and require a transformation towards a sustainable industrial model. Nevertheless, even smaller industries characterized by a relatively low absolute environmental impact, but with a high environmental *intensity*[1] – as the paper and fashion industries – are in need for action as urgently as large industries (Jungmichel, Schampel, & Weiss, 2017).

In sum, the linear supply chain, relying on large quantities of easily accessible but finite resources and energy, and consequently creating a sheer amount of waste, is unveiling its sustainability and feasibility limits and calling for a substantial transformation. As a matter of fact, the quest for a change of production systems towards a sustainable industrial model is needed not solely because of the concerning current ecological trends, but also because of the current macro-economic and regulatory outlooks requiring new – more resource efficient – business practices to stay competitive (De Angelis, Howard, & Miemczyk, 2018). The attractiveness of the circular economy model arises from the recognition that achieving a sustainable industrial system based on the implementation of a *more* efficient production system – which only reduces the amount of resources used and of fossil energy consumed per unit of manufacturing output – will still be unsustainable in the long run, as it will not alter the finite nature of the production inputs. This solution, as stated by the Ellen MacArthur Foundation (2013a), "can only delay the inevitable" and, therefore, "a change of the entire operating system seems necessary" (Ellen MacArthur Foundation, 2013a, p. 22). The circular economy is an industrial model which represents, indeed, a systemic change of the entire

[1] The environmental intensity is defined as "the environmental impacts related to the industry's turnover" (Jungmichel, Schampel, & Weiss, 2017, p. 10).

operating system, and can thus be a promising approach for reducing the existing global sustainability pressures (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).

2.3.2 From the Linear to the Circular Supply Chain

Transforming a supply chain from a linear to a circular configuration entails shifting from an industrial model based on the depletion of finite reserves to an industrial model which is restorative by intention and design (Ellen MacArthur Foundation, 2013a). A circular supply chain is designed on the basis of the 3R principles defined in *Section 2.2* of reducing, reusing, and recycling, and, taking a systemic perspective, "it replaces the concept of waste with the one of restoration and aims to decouple economic growth from the use of virgin resources" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 7). In a circular industrial model, resources circulate in the system as long as possible with maximum value extracted from them at each point in a product's lifecycle, thus reducing the need for virgin materials and waste (Genovese, Acquaye, Figueroaa, & Koh, 2017; Stahel, 2016). The pivotal point in the realization of the circular supply chain is the creation of a link between the upstream resource issues and downstream waste issues (Moriguchi, 2007), achieved through a paradigm shift in the redesign of material flows (Genovese, Acquaye, Figueroaa, & Koh, 2017). The circular economy, indeed, primarily focuses on material flows, encouraging fundamental changes in product design and supply chain operations, and in the production philosophy at large. However, albeit representing an innovating and promising opportunity towards a more sustainable industrial system, the circular economy leaves other concerning environmental impacts, as the ones related to energy usage and carbon emissions, unresolved (Genovese, Acquaye, Figueroaa, & Koh, 2017).

At the nano level, the implementation of a circular industrial system would push the design of a *reverse supply chain*, a concept developed as an adaptation of circular economy principles to supply chain management (Genovese, Acquaye, Figueroaa, & Koh, 2017). The reverse supply chain augments the forward supply chain with a series of product design, operations and end-of-life management activities implemented to retrieve a product at the end of its lifecycle and handle its disposal or reuse (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017; Genovese, Acquaye, Figueroaa, & Koh, 2017). A reverse supply chain is either an *open-loop* or a *closed-loop* system. In an open-loop supply chain, materials are recovered and reused by parties other than the original producers and deployed in the production of different products (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017). In a closed-loop system, the forward and reverse supply chains of a specific product are coordinated so that, at the end of their lifecycle, products are retrieved from consumers and returned to the original manufacturer, for the recovery of added value by the reuse of components and materials in the production of products of the same type (Genovese, Acquaye, Figueroaa, & Koh, 2017; Ellen MacArthur Foundation; Granta Design; Life, 2015a). The closed-loop supply chain enables products to re-enter the system as a production input through recycling, reuse or remanufacturing in order to maximize value creation over the product's entire lifecycle (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017). More specifically, a closed system is characterized by both the *reuse of goods* and the *recycling of materials*. The reuse of goods entails the design of long-life goods and product-life extension through the reuse of the product itself, or through repairing and remanufacturing activities. The recycling of materials is, instead, related to closing the loop between post-use waste and production (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). From this perspective, Bocken, De Pauw, Bakker and Van Der Grinten (2016) classified the strategies required for the cycling of resources at the supply chain level into two categories: *slowing loops*, with the aim of a slowdown of the flow of resources through the reuse of goods; and *closing loops*, with the aim of closing the resource loop between post-use and production through the recycling of materials.

In this context, the circular industrial model is characterized by a further distinction between *technical* and *biological* cycles, which relies on distinct capital-building strategies (Ellen MacArthur Foundation, 2016a). Such distinction is based on the identification of two possible alternatives for handling waste materials: reuse and recycling on one side, and dissipative loss on the other (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). Technical products, components and materials are designed to be restored at the highest possible quality and for as long as possible through repair and maintenance, reuse, refurbishment and remanufacture, and ultimately recycling, for a consecutive number of cycles of production. On the other hand, in biological cycles, non-toxic materials are designed to be restored into the biosphere while rebuilding natural capital, after being cascaded into different applications (Ellen MacArthur Foundation; Granta Design; Life, 2015a; De Angelis, Howard, & Miemczyk, 2018).

The Ellen MacArthur Foundation (2013a)'s model of the circular economy is shown if *Figure 2*. The model distinguishes between the technical and biological cycles and is based on the principles of the *power of the inner circle*, *circling longer*, *cascaded use* and *pure inputs*.

The *power of the inner circle* suggests that the larger cost savings in terms of material, labour, energy, capital and associated externalities are achieved by direct reuse, intended as the perpetuation of a product's original purpose (Ellen MacArthur Foundation, 2013b). In other words, the tighter the circle, the less a product has to be changed to return to use (in terms of reuse, refurbishment or remanufacturing activities), and therefore the less material usage in comparison to the linear production system (Ellen MacArthur Foundation, 2013a). The *power of circling longer* refers to keeping products, or their components and materials, in use as long as possible, increasing their durability by either maximizing the number of consecutive cycles, or extending the time spent within a single cycle (Ellen MacArthur Foundation, 2013a; Ellen MacArthur Foundation, 2013b). The *power of cascaded use* entails using materials discarded from one value chain as by-products, as virgin materials in other product categories (Ellen MacArthur Foundation, 2013b). The last principle, the *power of pure circles*, aims to enhance the impact of the first three by "rendering them fit for onward use" (Ellen MacArthur Foundation, 2013b, p. 35). The rationale behind this principle is that purity of materials and quality of products and components increase collection and redistribution efficiency (Ellen MacArthur Foundation, 2013a). In this sense, it is fundamental that a product's end-of-life is anticipated at its production phase, in the choice of materials, particularly avoiding material mixtures which inhibit reuse, remanufacture or recycle without causing a degradation of the material itself (Ellen MacArthur Foundation, 2013b).

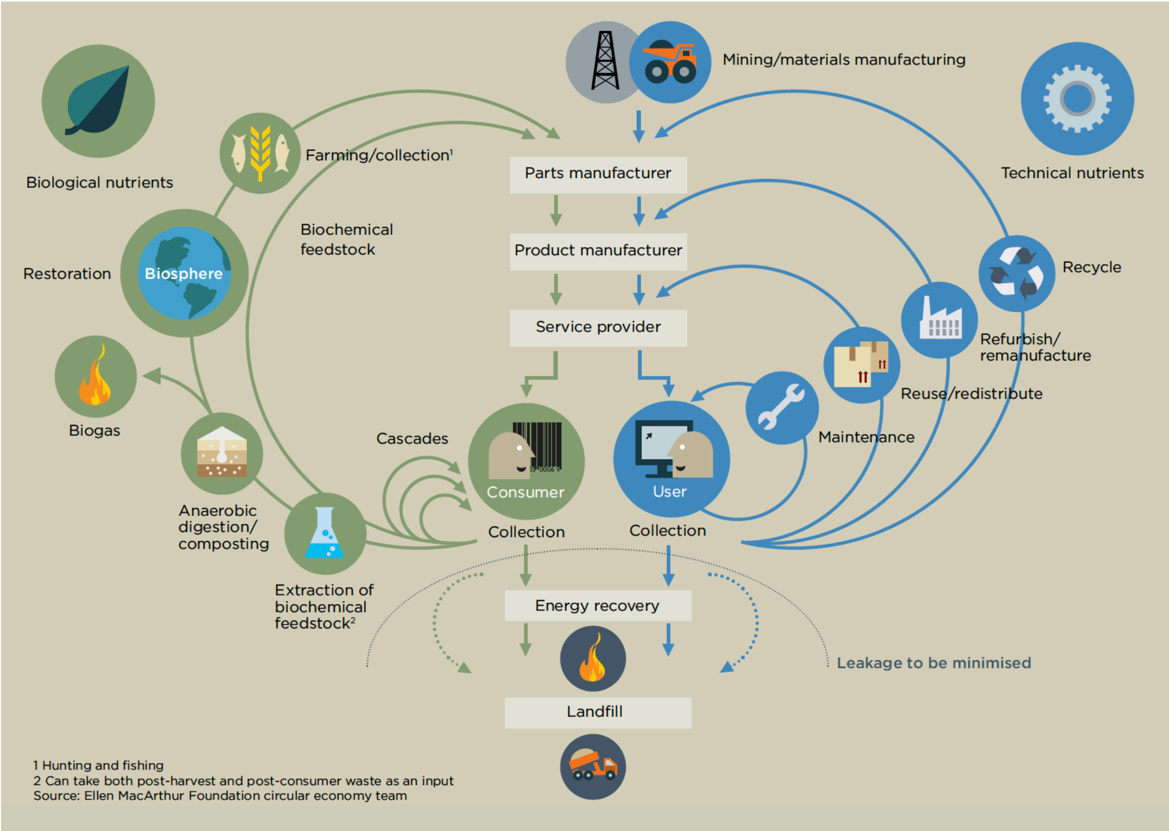

Figure 2 The Circular Economy. Source: (Ellen MacArthur Foundation, 2013a, p.24)

2.3.3 The Four Circularity Loops

Drawing from the Ellen MacArthur Foundation (2013a)'s circular economy model, four distinct circularity loops can be identified – i.e., from the inner to the outer loop, (1) *maintenance/prolong*, (2) *reuse/redistribute*, (3) *refurbish/remanufacture*, and (4) *recycle*. A circular industrial model is a combination of the four circularity loops, made possible by the use of specific product design strategies, innovative business models and technological innovation. The four circularity loops framework considered in this research follows the one developed by Saidani, Yannou, Leroy and Cluzel (2017) on the basis of the Ellen MacArthur Foundation's circular economy model (2013a), and is described below and summarised in *Table 2*.

Circularity Loops	*Description*
Maintenance/Prolong	Keeping products in circulation as long as possible, with as high value as possible
Reuse/Redistribute	Optimizing second-hand markets to avoid losing added value
Refurbish/Remanufacture	Returning a product to at least its original performance
Recycle	Designing for material recovery after losing an original product's added value

Table 2 Four Circularity Loops. Source: Saidani, Yannou, Leroy and Cluzel (2017)

Maintenance/Prolong

Maintenance represents the most inner circularity loop, and it refers to keeping the product in use as long as possible, with as high value as possible. Maintenance is achieved by designing the product for longevity, upgradeability and sharing (Saidani, Yannou, Leroy, & Cluzel, 2017).

Reuse/Redistribute

The term *reuse* refers to a series of operations performed to put a product at the end of its lifecycle back into service for the same purpose and in its original form, with or without repair or remediation (Ellen MacArthur Foundation; Granta Design; Life, 2015a; Cole, Gnanapragasam, & Cooper, 2017). As the Ellen MacArthur Foundation (2015a) describes, reselling a product in its entirety represents the strategy that, together with extending its use phase, creates the greatest economic benefits compared to a linear model, in that it allows to capture new markets (e.g., second-hand markets) and create new revenue streams (e.g., from maintenance and repair offered as services). If a product cannot be reused as a whole, individual parts and components can still be reused in a functional way (Ellen MacArthur Foundation; Granta Design; Life, 2015a).

Refurbish/Remanufacture

Refurbishment is defined by the Ellen MacArthur Foundation (2015a) as the process of "returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making cosmetic changes to update the appearance of a product, such as changing fabric or painting" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 16). *Remanufacture*, instead, is defined as the process of "disassembly and recovery at the sub-assembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new one. This process includes quality assurance and potential enhancements or changes to the components" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 16). Refurbish and remanufacture represent efficient means of material recirculation in that the energy and virgin raw materials deployed are substantially less than those to produce a new product, and the energy associated with the original production process that can be retained by refurbish and remanufacture is more than that retained by recycling. At the same time, though, refurbish and remanufacture are less efficient options than reuse, as component reuse results in lower overall material and energy consumption (Nasr & Thurston, 2006).

The remanufacturing process has long been researched and consists of the six key steps of disassembly, cleaning, inspection, reconditioning, reassembly and final testing. These steps can be grouped into four fundamental activities of *part interfacing* (disassembly and reassembly), *cleaning*, *quality assurance* (inspection and testing) and *damage correction* (repair, refurbishment, and replacement) (Sundin, 2004).

Recycle

Recycle defines the process of "recovering materials for the original purpose or for other purposes" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 16). In the recycling process, waste is recovered and materials feed back into the process as crude feedstock, either for the original purpose or for other purposes (Ellen MacArthur Foundation; Granta Design; Life, 2015a). As previously stated, the recycling process alters the physical form of materials, but is able to preserve part of the value embedded in the discarded materials. It is considered to be the least efficient material recirculation strategy, but it is still preferred to energy from waste and disposal (Park & Chertow, 2014).

The recycling process can be categorized in different kinds of recycle, and each of them either fits or not the circular industrial system. In particular, Bocken, De Pauw, Bakker and Van Der Grinten (2016) identified four different types of recycling process (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016):

- *Primary recycling*, also referred to as *closed-loop recycling* or *upcycling*, entails the mechanical reprocessing of discarded materials into a product with equivalent or improved properties, and it is required for the implementation of a technical cycle.
- *Secondary recycling*, also referred to as *downcycling* or *downgrading*, entails the mechanical reprocessing of discarded materials into products of lower properties and low value, and therefore it does not fit the circular economy.
- *Tertiary recycling*, also referred to as *chemical* or *feedstock recycling*, is about the recovery of the chemical constituents of materials. More specifically, it represents "the structural breakdown of materials into their original raw core components (for instance depolymerisation) and consecutive build-up (repolymerisation) of material with properties equivalent to the original material" (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016, p. 312), and it is required for the implementation of a technical cycle.
- *Quaternary recycling* is concerned with the recovery of energy from materials and includes thermal recycling, energy recovery and energy from waste. This type of recycling process does not fit the circular economy, as only part of the energy content of a material is used again.

The link between the circular principles of the *power of the inner circle*, *circling longer*, *cascaded use* and *pure materials*, and the four circularity loops described in this section, is obtained through the following four circular practices aimed to restore material flows (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 10):

- "using feedstock from reused or recycled sources;
- reusing components or recycling materials after the use of the product;
- keeping products in use longer (e.g., by reuse/redistribution);
- making more intensive use of products (e.g., via service or performance models)".

In this light, the strategies which create the most economic and environmental value are those which retain the most of a product's embedded materials, energy and labour. Therefore, in accordance with the principle of the *power of the inner circle*, end-of-life strategies should favour, hierarchically, maintenance to prolong durability and reuse with little or no change, because these two strategies recover most of the original product's value and spend the less new material, energy and labour. When maintenance and reuse can no longer be pursued, refurbishment and remanufacturing should be preferred to recycle, for that in the recycling process materials normally lose quality and, therefore, their suitability for use in subsequent cycles significantly decreases (De Angelis, Howard, & Miemczyk, 2018).

This conceptualization is consistent with the *solid waste management hierarchy* and the *sustainable materials management* frameworks developed by the United States Environmental Protection Agency. The solid waste management hierarchy places reduction and reuse at the top of the hierarchy, followed by recycling and composting, which still preserve some of the embedded value of discarded materials albeit changing their physical form, and finally by incineration and landfill, which are the least conserving (Park & Chertow, 2014; USEPA, 1989). The sustainable materials management framework takes a step further in the material conservation effort, developing an integrative framework for managing materials, regardless of the state of materials (i.e., if it waste or non-waste material), thus shifting focus to long-term, multiple, and system-wide environmental impacts (USEPA, 2009; Park & Chertow, 2014).

2.3.4 Circular Product Design

The circular economy represents an attempt to create a new metabolism that allows for self-sustaining methods of production in which materials circulate within the system as long as possible (Genovese, Acquaye, Figueroaa, & Koh, 2017). The creation of such metabolism requires companies to implement a circular design, consisting of improvements in material selection and product design to facilitate the recovery of components and materials, and innovative business models to provide incentives and enable the collection of products (Ellen MacArthur Foundation; Granta Design; Life, 2015a; Ellen MacArthur Foundation, 2013a). Product design represents a particularly important indicator of the circularity potential of a product, in that it determines the longevity, repairability, suitability for remanufacture and refurbishment and recyclability of the product, as well as the proportion of recycled and renewable material in the product (EEA, 2017).

Moreno, De los Rios, Rowe and Charnley (2016) developed a framework of design strategies for a circular economy, which brings together the existing body of literature on Design for Sustainability (DfX), considered by the authors as a precursor to circular design, with the current research on circular business models. The framework includes the work from Bocken, De Pauw, Bakker and Van Der Grinten (2016), which considers the existing literature on consumer product design and links it to circular business models (Moreno, De los Rios, Rowe,

& Charnley, 2016). The framework, described below, distinguishes among *Design for Resource Conservation, Design for Slowing Resource Loops* and *Whole Systems Design*.

Design for Resource Conservation

Design for Resource Conservation focuses both on (1) closing resource loops and (2) reducing resource consumption. On one hand, closing resource loops entails designing for technical and biological cycles, as well as for dis- and reassembly (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). As previously described, the distinction between technical and biological cycles lies in the different handling of waste materials. As technical and biological materials entail two fundamentally distinct product design strategies, the scope of this research is restricted to the analysis of product circularity in technical cycles, exclusively. Design for technical cycles is suitable for "products of service" (as opposed to "products of consumption"), and such strategy aims to design products in a way that technical materials and components can continuously and safely be recycled into new materials or products. As mentioned, the types of recycling process which enable the design for technical cycles are primary and tertiary recycling (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).

On the other hand, reducing resource consumption is concerned with production quality control, reduction of production steps, miniaturizing and light weighting, eliminating yield loses, material, resources, parts and packaging, and reducing material and resource use (Moreno, De los Rios, Rowe, & Charnley, 2016).

Design for Slowing Resource Loops

Design for Slowing Resource Loops includes strategies for (1) designing long-life products and (2) product-life extension. Designing long-life products means (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016; Moreno, De los Rios, Rowe, & Charnley, 2016):

- enhancing reliability and durability of the product (by designing on demand or on availability and designing the appropriate lifespan of products and components);
- ensuring product attachment and trust (by creating timeless aesthetics, designing for pleasurable experiences and allowing for a meaningful design).

Designing for product-life extension, instead, includes focusing on (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016):

- the ease of maintenance, which is the performance of inspection and servicing tasks to retain the product's functional capabilities; and the ease of repair, aimed to restore a product to sound condition after decay or damage;
- upgradability and adaptability, to ensure that the product can continue being used under changing conditions;
- standardization and compatibility, referred to creating a product with parts and components that fit other products as well;
- dis- and reassembly, to ensure that the product, its parts and components can be separated and reassembled easily.

Moreno, De los Rios, Rowe and Charnley (2016) augment this conceptualization by introducing the design for dematerializing products as a strategy to design long-life products, characterized by the design for product-service systems and for swapping, renting and sharing – which will be further analysed in this thesis as business model strategies to slow resource loops. Moreover, the authors introduce the design for multiple cycles, as an additional strategy for slowing resource loops. The design for multiple cycles focuses on resource recovery by designing for easy end-of-life cleaning, collection and transportation of recovered materials and resources, designing for remanufacturing and dis- and re- assembly and designing for upcycling and recycling (Moreno, De los Rios, Rowe, & Charnley, 2016).

Whole Systems Design

Whole Systems Design is the design for systems change, focused on reducing environmental backpacks by designing for the entire value chain and for local value chains, and on implementing regenerative systems by designing for biomimicry and for biological and *technical cycles* (Moreno, De los Rios, Rowe, & Charnley, 2016).

The following table provides a summary of the circular product design strategies described above, based on the frameworks developed by Bocken, De Pauw, Bakker and Van Der Grinten (2016) and Moreno, De los Rios, Rowe and Charnley (2016).

Design for Resource Conservation	Closing Resource Loops	Designing for Technical and Biological Cycles
	Reducing Resource Consumption	Production Quality Control
		Reduction of Production Steps
		Miniaturizing and Light Weighting
		Eliminating Yield Loses
		Reducing Material and Resource Use
Design for Slowing Resource Loops	Designing Long-Life Products	Enhancing Reliability and Durability of the Product
		Ensuring Product Attachment and Trust
	Designing for Product-Life Extension	Ease of maintenance
		Upgradability and Adaptability
		Standardization and Compatibility
		Dis- and reassembly
Whole Systems Design	Design for Systems Change	Designing for the Entire Value Chain and for the Local Value Chains
	Implementing Regenerative Systems	Designing for Biomimicry

Table 3 Summary of Circular Product Design. Source: Bocken, De Pauw, Bakker and Van Der Grinten (2016); Moreno, De los Rios, Rowe and Charnley (2016)

2.3.5 Circular Business Models

As mentioned in the previous section, the design for a circular economy should not only rely on the rethinking of material usage and product design but also evaluate the context of the business model that a product is being designed for. The business model refers to the way a firm does business, and specifically the way in which a firm intends to create and capture value. Using the three-box business model framework, fundamental factors characterizing a business model are (1) the value proposition, referred to the product/service offering; (2) the value creation and delivery, i.e., how the value is provided; and (3) the value capture, specifically referred to how the company makes money. Business models are considered an important driver for innovation, and every product design rethinking should, therefore, be coupled with the development of the right business model (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). As the circular economy represents, indeed, a radical change in companies' industrial systems, proper business models strategies fitting the approaches of slowing and closing loops, need to be implemented. Bocken, De Pauw, Bakker and Van Der Grinten (2016) developed a framework of key business model innovations to slow and close resource loops, which is hereto combined with the circular business models categorization developed by Esposito, Tse and Soufani (2018).

Business Models for Slowing Loops

Business models for slowing loops aim to encourage long product life and the reuse of products. The first business model in this category is the *Access and Performance Model*, which delivers the capability or services (access and performance) – rather than the ownership of physical products – to satisfy users' needs (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). This model, also referred to as *Product Service System*, takes several forms – as pay for use, leasing, rental, and performance agreement (Esposito, Tse, & Soufani, 2018). Service maintenance is handled by the manufacturer or retailer, whose incentives come from the increasing profits they can generate from durability, energy efficiency, reusability and reparability of their products (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).

A second business model for slowing resource loops is the *Extending Product Value Model*, aimed to exploit the residual value of products through remanufacturing or repair, and to deliver an affordable *as new* product. Such business model may be developed by the original manufacturer or by third party manufacturers through take-back systems and collaborations to enable consistent product returns (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). As the *Access and Performance Model*, the *Extending Product Value Model* can be implemented in several ways. For instance, through refurbishment, which is the restoration of products to their original state for reselling to price-sensitive clients; or by upgrading, i.e., adding new features, functionality or fashion to the original products, to target customers interested in consuming content, functions and style rather than the products themselves. Fundamental for the implementation of an *Extending Product Value Model* is to have in place take-back, trade-in and buy-back to remarket, to facilitate collecting pre-owned goods to trade or resell (Esposito, Tse, & Soufani, 2018).

The *Classic Long-Life Model* aims to produce high quality, long lasting products through durable product design and high levels of service (as repair and maintenance) that make products reparable and reusable. Similarly, the fourth and last business model type in the slowing resource loops category, *Encourage Sufficiency Model*, includes solutions to reduce end-user consumption, by actively taking a non-consumerist approach to sales and promotion. The manufacturer delivers high quality, long-lasting products to allow users to use them as long as possible through high levels of service. The *Classic Long-Life Model* and the *Encourage Sufficiency Model* are both premium business models, in which the price covers the long-term service and product warrantee (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). These two models can be implemented by strategies as build to last, refill and repair (Esposito, Tse, & Soufani, 2018).

Business Models for Closing Loops

Business models for closing loops aim to capture value from recovering by-products and waste, in order to make them a resource fully integrated in the business model, rather than a problem to be dealt with. Resource return chains transform waste into value through recycling and reincarnation (Esposito, Tse, & Soufani, 2018). The first business model in this category is the *Extending Resource Value Model*, which exploits the residual value of resources – while reducing material costs – by collecting and sourcing otherwise wasted materials. It can be implemented through new collaborations and take-back systems aimed to collect or source materials (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).

The second model for closing loops is the *Industrial Symbiosis Model*, concerned with turning waste outputs from one product category into feedstock for another. This model allows for a reduction of overall operating costs and risks, through collaborative agreements for sharing communal services and exchanging by-products (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016).

The following table provides a summary of the circular business model strategies described above, based on the frameworks developed by Bocken, De Pauw, Bakker and Van Der Grinten (2016) and Esposito, Tse and Soufani (2018).

Slowing loops	Access and Performance Model
	Extending Product Value Model
	Classic Long-Life Model
	Encourage Sufficiency Model
Closing loops	Extending Resource Value Model
	Industrial Symbiosis Model

Table 4 Summary of Circular Business Models. Source: Bocken, De Pauw, Bakker and Van Der Grinten (2016); Esposito, Tse and Soufani (2018)

2.3.6 Technological Revolution

During the last decade, the technology revolution – by many regarded as the fourth industrial revolution – has had a considerable impact on individuals, businesses and society at large (Ellen MacArthur Foundation, 2016b). Digital technology is already embedded in a wide variety of products, and the benefits businesses can reap when deploying digitization in their product design or supply chain are developing fast. The technology revolution represents a key enabler of the circular economy, particularly at the nano level (Ellen MacArthur Foundation; SUN; McKinsey, 2015b), and the interplay between circular business practices and digital technology creates new opportunities for value creation (Ellen MacArthur Foundation, 2016a), leading to resilient, decentralised and self-repairing systems (Ellen MacArthur Foundation, 2016b). Intelligent assets are defined as "physical objects that are able to sense, record and communicate information about themselves and/or their surroundings" (Ellen MacArthur Foundation, 2016b, p. 15), therefore able to provide knowledge about the location, condition and availability of an asset. As stated by Michael Spence, professor in Economics and Business at the New York University, "the Internet of Things combined with big data and data analytics has the potential to turbocharge promising circular economy models, in part via the impact on the efficiency of use, maintenance and longevity of assets*"* (Ellen MacArthur Foundation, 2016b, p. 9).

The Ellen MacArthur Foundation (2016b) conducted a comprehensive research to evaluate the potential benefits of combining circular economy value drivers and intelligent assets value drivers. Product design and supply chain operations may be substantially improved in a more circular direction by exploiting intelligent assets at several levels (Ellen MacArthur Foundation, 2016b). One of the most advantageous applications of intelligent assets in the context of a circular supply chain is *predictive maintenance*. Intelligent assets and comprehensive real time data, providing knowledge about the condition of an asset, allow for effective predictive maintenance schemes in order to both extend the product's lifecycle or enable the reutilization of either the product itself or its resources (Ellen MacArthur Foundation, 2016b). Intelligent assets also facilitate *redefining design*. The aggregation of Internet of Things (IoT)-generated knowledge on the composition and real time condition of an asset allows to change and improve product design, creating insights into more productive, durable and long-lasting product design, thus extending the product's lifecycle (products are more durable and easier to maintain), and enabling further looping (product design is improved for remanufacturing and design for disassembly) (Ellen MacArthur Foundation, 2016b). Concerning reverse logistics and remanufacturing, due to the volatile demand and supply of used products and components, and the varying conditions of the returned products, these activities have long been associated with several risks. The ability – provided by intelligent assets – to collect data about a product's condition and current market situation, and an analytical model to make sense of such information, facilitate *decision making for future loops*, i.e., decision making on the next use cycle for returned products (Ellen MacArthur Foundation, 2016b). Intelligent assets also enable the *optimization of route and reverse logistics planning*. New tracking technologies providing information on the location and condition of assets improve supply chain and logistics operations' transparency and visibility. Such information enables the optimization of the delivery route and reverse logistics, allowing for an extension of the product's lifecycle by minimizing damages and losses, and for the looping and cascading of products across multiple lifecycles through the ability to quantify recovery value on a product-specific level (Ellen MacArthur Foundation, 2016b). Concerning *waste management and recycling*, sensing technology improves the precision of sorting activities, thus allowing for higher recycling yields, by providing insights into the composition of multiple types of materials (Ellen MacArthur Foundation, 2016b). Lastly, intelligent assets provide insights into the complex dynamics of natural resources, enabling to increase asset productivity and the regeneration of land, thus creating an *intelligent natural capital* (Ellen MacArthur Foundation, 2016b).

	Intelligent Asset Value Drivers		
Circular Economy Value Drivers	*Knowledge of the location of the asset*	*Knowledge of the condition of the asset*	*Knowledge of the availability of the asset*
Extending the use cycle length of an asset	Guided replacement service of broken component Optimized route planning to avoid vehicle wear	Predictive maintenance and replacement of failing components prior to asset failure Changed use patterns to minimize wear	Improved product design from granular usage information Optimized sizing, supply and maintenance in energy systems from detailed use patterns
Increasing utilization of an asset or resource	Route planning to reduce driving time and improve utilization rate Swift localization of shared assets	Minimized downtime through predictive maintenance Precise use of input factors in agriculture	Automated connection of available, shared asset with next user Transparency of available space to reduce waste
Looping/cascading an asset through additional use cycles	Enhanced reverse logistics planning Automated localization of durable goods and materials on secondary markets	Predictive and effective remanufacturing Accurate asset valuation by comparison with other assets Accurate decision-making for future loops	Improved recovery and reuse/repurposing of assets that are no longer in use Digital marketplace for locally supplied secondary materials
Regeneration of natural capital	Automated distribution systems of biological nutrients Automated location tracking of natural capital	Immediate identification of signs of land degradation Automated condition assessment	

Table 5 Summary of Digital Technology Applications for the Circular Economy. Source: Ellen MacArthur Foundation (2016b, p. 30)

3. Theoretical Framework

3.1 The Supply Chain as a Static System

The concepts of supply chain and supply chain management have long had particular relevance in the literature. This is shown by the fact that many periodicals, either on manufacturing, distribution, marketing, customer management or transportation, gave increasing space to articles reporting on supply chain management or supply chain management related topics (Mentzer, et al., 2011). Overall, some authors define the supply chain management in operational terms involving the flow of materials and products, others view it as a management philosophy, and others in terms of a management process (Tyndall, Gopal, Partsch, & Kamauff, 1998). Some authors conceptualize the supply chain management in different ways: for instance, as a form of integrated system between vertical integration and separate identities on one side, and as a management philosophy on the other (Copper & Ellram, 1993).

Given this ambiguity, Mentzer, et al. (2011) presented a first attempt to make the concept of supply chain management clearer. As a matter of fact, in their research, they reviewed, classified, and synthesized some of the most widespread definitions of supply chain and supply chain management in both academia and practice in order to reach a comprehensive definition. The first definition presented is the following: the supply chain is “a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer” (Mentzer, et al., 2011, p. 4). More specifically, there exist three degrees of complexity of supply chains: a supply chain might be viewed either as 1) direct supply chain; 2) extended supply chain; or 3) ultimate supply chain. The simplest supply chain is referred to as direct supply chain and it includes “a company, a supplier, and a customer involved in the upstream and/or downstream flows of products, services, finances, and/or information” (Mentzer, et al., 2011, p. 4). The extended supply chain consists of “suppliers of the immediate supplier and customers of the immediate customer, all involved in the upstream and/or downstream flows of products, services, finances, and/or information” (Mentzer, et al., 2011, p. 4). Lastly, the term ultimate supply chain includes “all the organizations involved in all the upstream and downstream flows of products, services, finances, and information from the ultimate supplier to the ultimate customer” (Mentzer, et al., 2011, p. 4), including, among others, third party financial providers or third party logistics.

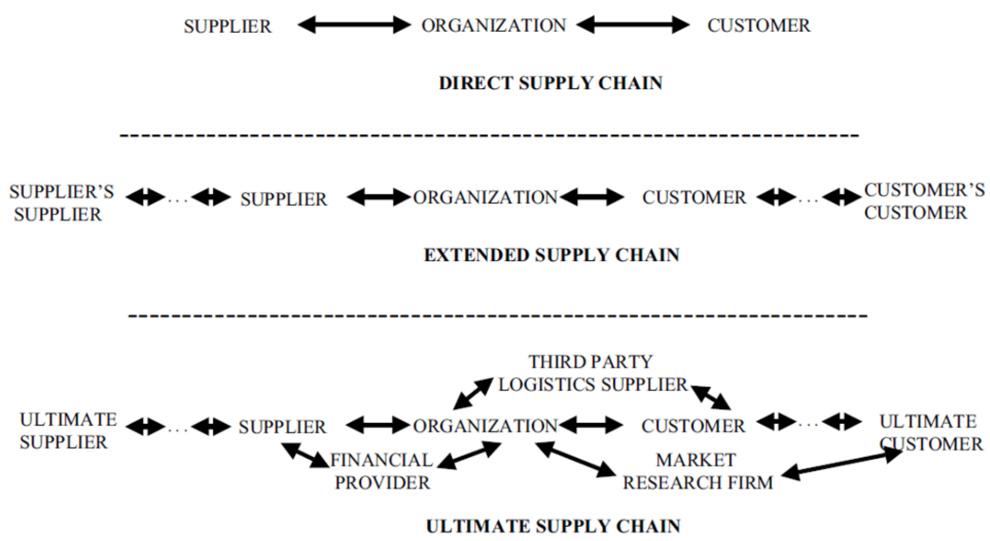

Figure 3 Types of Channel Relationships. Source: Mentzer, et al., (2011, p. 5)

If on the one side there are supply chains, defined as phenomena that exist in businesses, on the other, there is the management of these supply chains required by organisations within the supply chain. In other words, the supply chain management might be defined as the discipline which aims at managing the supply chain phenomenon. Although definitions of supply chain management differ across authors, they can be classified into three categories: a management philosophy, the implementation of a management philosophy, and a set of management processes (Mentzer, et al., 2011). The supply chain management as a philosophy entails viewing the supply chain as a single entity, rather than a set of different and separated parts performing their own functions. This means that each node in the supply chain has an impact – either direct or indirect – on the performance of every other node in the supply chain and eventually on the entire supply chain performance. For this reason, the operations and strategic capabilities of each company along the supply chain should be synchronised and should converge into a unified whole, with the final goal of creating sources of customer value and, eventually, customer satisfaction (Mentzer, et al., 2011).

In order to behave consistently with such philosophy, companies must follow these practices: a) integrated behaviour in order to incorporate customers and suppliers; b) mutually sharing information – especially regarding planning and monitoring processes; c) mutually sharing risks and rewards for a long-term focus and cooperation among the members; d) cooperation in focal activities such as planning and controlling activities to evaluate the performance of the members and of the supply chain as a whole; e) having the same goal and the same focus on serving customers as a form of policy integration in order to avoid redundancy and overlap, being more effective and efficient; f) integration of processes, being them sourcing, manufacturing and distribution; g) partners must build and maintain long-term relationships, e.g., forming strategic alliances (Mentzer, et al., 2011).

Lastly, supply chain management was defined as a set of management processes, where *process* is intended as a set of activities needed to produce a specific output, to manage relationships, information and materials or the way in which goods and services move through the supply chain structure. This means that – differently from the traditional functions – each process in the process approach aims at meeting customers' expectations and at reaching customers' satisfaction (Mentzer, et al., 2011).

Therefore, supply chain management refers to "the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole" (Christopher, 2016) or, in other words, supply chain management is:

> The systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole (Mentzer, et al., 2011, p. 18).

Moreover, businesses must take into account the concept of supply chain orientation, which is:

> The idea of viewing the coordination of a supply chain from an overall system perspective, with each of the tactical activities of distribution flows seen within a broader strategic context (what has been called SCM as a management philosophy). The actual implementation of this orientation, across various companies in the supply chain, is more appropriately called Supply Chain Management (Mentzer, et al., 2011, p. 11).

More specifically, supply chain orientation is defined as "the recognition by an organization of the systemic, strategic implications of the tactical activities involved in managing the various flows in a supply chain" (Mentzer, et al., 2011, p. 11), taking into account the effects of its actions on the upstream and downstream flows of goods, finances and information.

3.2 The Supply Chain as a Complex Adaptive System

Although the early literature on the supply chain management considered the supply chain as a static system, the more recent literature presents a different view. More specifically, Carter, Rogers and Choi (2015) see the supply chain as a *complex adaptive system* (CAS). In this view, the supply chain is relative and characterized by a visibility horizon, and its actors do not have control – or agency – on the whole supply chain (Carter, Rogers, & Choi, 2015). These concepts are presented in six foundational premises of the supply chain which give structure and boundaries to the subject. The foundational premises are the following:

The Supply Chain is a Network

The first foundational premise moves the focus from the supply chain seen as buyer-supplier dyad, to triads and eventually to the extended network. Indeed, it claims that the supply chain is a network, consisting of nodes and links. Nodes are defined as "an establishment which is an agent that has the ability to make decisions and maximize its own gain within the parameters in which it operates (e.g., manufacturers, warehouses, transportation carriers, and financial institutions)", while links are defined as "the connection between two nodes" and they "represent transactions consisting of the flow of materials, information, and/or finance between nodes" (Carter, Rogers, & Choi, 2015, p. 90).

The Supply Chain is a Complex Adaptive System

The second foundational premise states that "the supply chain as a network operates as a complex adaptive system (CAS), where every agent grapple with the tension between control and emergence" (Carter, Rogers, & Choi, 2015, p. 91). More specifically, inside the supply chain, every agent as a node interacts both upstream toward its suppliers and downstream toward its customers. Nonetheless, in both directions, the visibility of the agent is limited and what lies beyond its visibility range emerges for the agent. Hence, the supply chain is not only simply a system, rather it is a dynamic, complex, and difficult to predict and control system or, in other words, a CAS (Carter, Rogers, & Choi, 2015).

The Supply Chain is Relative

The third foundational premise underlies that within the visual range of each agent in the supply chain, there are many supply chains. As a matter of fact, the agent is at the convergence of many supply chains; hence, it is crucial to define a supply chain in relation to its agent, i.e., the company, and to the specific input or output, i.e., referent or unit of analysis. In other words, there is not an absolute supply chain, but the supply chain is relative to its reference points (Carter, Rogers, & Choi, 2015).

There is a Physical and a Support Supply Chain

The fourth foundational premise offers a conceptualisation of the structure of the supply chain and it suggests a more precise mapping. The supply chain consists of both a physical and a support supply chain. In the former, the node is an agent with a permanent, physical location where activities occur that add form, place, and/or time utility, i.e., suppliers, focal firm and customers; in the latter, products do not flow through nodes but these nodes support the physical supply chain, being, for instance, either carriers or financial institutions (Carter, Rogers, & Choi, 2015).

The Supply Chain is Bounded by a Fuzzy Horizon

The fifth foundational premise states that the supply chain "is bounded by the visible horizon of the focal agent" (Carter, Rogers, & Choi, 2015, p. 93). This principle underlies that one agent cannot have complete information about and be aware of all the upstream and downstream nodes and links. Therefore, this makes the supply chain more complicated to be managed and controlled. This principle completes the third one, suggesting that the supply chain is not only relative to a focal agent or product, but also bounded in the sense that every agent has a limited knowledge of all the other nodes. The supply chain still continues beyond the visible horizon, hiding additional nodes and links. However, as the sixth and last foundational premise reports, "the visible horizon of the focal agent is subject to attenuation – i.e., the boundary of supply chain become less clear – where distance is based on factors including physical distance, cultural distance, and closeness centrality" (Carter, Rogers, & Choi, 2015, p. 94).

3.3 The Circular Economy Challenge

As mentioned in the *Conceptual Framework*, the conceptualization of the circular economy relies on a system thinking perspective: Moving to a circular industrial model entails a systemic change of the supply chain as a whole. Taking into consideration the Ellen MacArthur Foundation (2013a)'s model of the circular economy, it is clear how achieving circularity needs leveraging different supply chain operations in order to implement the four circularity loops of maintaining, reusing, remanufacturing and recycling – thus requiring the involvement of different actors at the different stages of the supply chain. Nevertheless, this systemic perspective seems to contradict Carter, Rogers and Choi (2015)'s theory that sees the supply chain as a CAS. In this view, the supply chain is relative and characterized by a visibility horizon, and its actors do not have control – or agency – on the whole supply chain (Carter, Rogers, & Choi, 2015), making the implementation of a circular industrial system seem difficult to realize.

As a matter of fact, the systemic change necessary to implement a circular economy model goes beyond the individual firm, requiring partnerships and networks of companies operating at different points in the supply chain. Collaboration among them is, indeed, fundamental, as it allows companies to synchronize investments and logistics infrastructure, and to create synergies of skills and knowledge (Preston, 2012). It can be argued, then, that the circular economy is more easily studied, and possibly actually implemented, if a traditional view of the supply chain as a static system – as the one proposed by Mentzer, et al. (2011) – is taken. According to this theoretical perspective, it is possible to have a clear understanding of how both suppliers and customers operate at the different stages along the supply chain (Mentzer, et al., 2011), enabling that system perspective that would allow for the study of the supply chain as a whole and to reach the systemic change that the implementation of a circular industrial model necessitates.

Nevertheless, viewing the supply chain as a static system does not provide a comprehensive understanding of the network relationships, and of the power relations and agency existing among actors characterizing the system itself. Supply chains for most products today involve multiple countries, to the point that they can be defined *global* supply chains. It is exactly in this context that assuming a traditional view of the supply chain becomes challenging. As described by Carter, Rogers and Choi (2015), the boundaries of the supply chain become less clear as the physical and cultural distance of the focal firm from other agents increases. As a consequence, the more the supply chain is bounded by these geographical barriers, the shorter the focal firm's visibility horizon is. In turn, these barriers make it complicated for the focal firm to take a holistic view of the whole product supply chain. This is a key challenge that needs to be addressed, in order to develop a model for the circular economy which overcomes the complexities characterizing global supply chains.

To this end, full use of new technologies enabling information collection, analysis and sharing between companies is a catalyst. Moreover, if major global companies – having considerable influence over their suppliers, who can be affected by a change in policy – took a serious step towards circular approaches, it would be possible to generate an impact which would be felt across the economy. However, further international cooperation is also crucial for progress on the circular economy, as separate domestic policies can only address part of the challenges faced by global supply chains. Key technologies will need to spread across borders and be adapted to local needs, and coordination of national policies in key areas could help easing competitiveness concerns and reducing the costs of implementation for business (Preston, 2012).

In this context, it is fundamental to develop an overall understanding of how far companies are in their shift towards a circular industrial model, starting from products to broader implementation levels. This would allow for an enrichment of the body of literature on the circular economy, extending the existing knowledge on the roles that the different actors along the supply chain play in the implementation of a circular industrial model, by looking at its catalysts for each level of implementation (macro, meso, micro and nano). The development of an instrument that measures the degree of product circularity may represent an initial step, albeit small, towards the creation of an extensive and growing research on the circular economy, possibly paving the way for the steady increase of its implementation, not only at the local but also at the global level.

4. Research Scope and Literature Review

4.1 Problem Formulation

The circular economy represents a promising response to the existing global sustainability pressures (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016), which is gaining momentum in political and business circles (De Angelis, Howard, & Miemczyk, 2018). Nevertheless, the existing literature on the circular economy is considered more embryonic: still fragmented and spread across a number of more established fields, and not yet focused on the implementation and the potential implications of the circular economy for business models and supply chains (De Angelis, Howard, & Miemczyk, 2018). In particular, as described more into detail in *Section 4.3*, academic circles still lack an effective measurement tool to assess the degree of circularity at its different systemic levels, and especially at the micro level. Furthermore, the importance of product circularity in the context of the circular economy creates the need to develop a nano indicator, that can measure the degree of circularity at the single product level (Saidani, Yannou, Leroy, & Cluzel, 2017).

The objective of the present research is, therefore, that of creating an instrument which can measure the degree of product circularity, from the perspective of the focal firm in the context of its supply chain. The research is based on the five cornerstones identified by Saidani, Yannou, Leroy and Cluzel (2017), as crucial factors in the development of a circularity measurement framework. First, the instrument should be (1) systemic by design, "to ensure a holistic approach – i.e., to consider the whole complexity of circular economy paradigm during product circularity measurement" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 12), and (2) integrated and operational, "to be fit with industrial practices during design and development phases" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 12). Second, the instrument should be (3) adaptive and flexible, "to have the ability to consider different products from diverse industrial sectors" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 12) and characterized by an (4) intuitive user interface, "to be effectively and efficiently used by practitioners" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 12). Finally, the ultimate feature, (5) connection to sustainable pillars, means that the instrument should not be a goal in itself but a means to achieve a more sustainable development (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 12).

4.2 Research Question

As anticipated in *Section 4.1*, the aim of the study is to assign a measure to the circular economy, thus providing the academia with an effective instrument, which can measure the degree of product circularity, in order to deepen the understanding of circular industrial models, their implementation and implications. Such a measurement tool would facilitate the analysis of product circularity combined with other relevant sustainability measures. The rationale behind this study is that the academia still lacks an extensive and comprehensive body of literature on the circular economy, and a measurement tool would potentially facilitate and encourage conducting further studies, investigating the implementation and performance of circular models, evaluating how far supply chains are in shifting from linear to circular industrial systems, and possibly understanding the requirements in different industries to achieve a certain degree of product circularity.

The development of the research question addressed in this study was based on several defining factors. First, the *empirical focus* of the research is the degree of circularity measured at the product level from the perspective of the focal firm in the context of its supply chain, specifically addressing industries characterized by technical cycles. The research is based on several parameters defined in the literature as the catalysts, or enablers, of the circular economy. Such parameters, described in the *Research Design and Methodology*, are product design, business model, technological revolution, materials management, and promotion and customer involvement. Second, the *theoretical focus* of the research is the acknowledgment that implementing a circular economy model in an industrial context defined as a complex adaptive system is challenging, hence it requires the development of a more comprehensive theoretical background for the circular economy, possibly creating a separate established field for circular economy-related research. Third, the *research design and approach* adopted to develop the instrument, further described in the *Research Design and Methodology*, is a sequential exploratory analysis based on a mixed methods approach, specifically an instrument development method. In consideration of all the above-described factors, this study addresses the following research question:

How to develop an instrument to measure the degree of circularity of a product for the focal company in the context of its supply chain based on parameters defined as the catalysts of product circularity.

4.3 Related Work

4.3.1 Other Circularity Indicators

As mentioned, with the spread of the circular economy as a potential solution to the increasing global sustainability pressures, it is necessary for businesses to be guided in their evolution from a linear to a circular economy. Therefore, methods and tools must be defined and developed, in order to support businesses in assessing and enhancing their product circularity performance (Saidani, Yannou, Leroy, & Cluzel, 2017) and evaluating whether the circular economy principles are leading to meaningful change (Cayzer, Griffiths, & Beghetto, 2017). Nonetheless, this necessity is barely addressed, and, to date, circularity measures are for the majority conducted by consultancy firms (as, for instance, the Circle Scan & Circle Assessment developed by Circle Economy Cooperative or the Closed-Loop Calculator developed by Kingfisher). Moreover, these measures mostly rely on the business and marketing expertise of the firms which developed them and do not root on strong academic and scientific research methods (Saidani, Yannou, Leroy, & Cluzel, 2017).

Most existing circular economy indicators focus on the macro and meso levels, but hardly on the micro-level (Ghisellini, Cialani, & Ulgiati, 2016). Furthermore, the existing micro indicators present some weak points: on the one hand, they are mainly based on cleaner production and green consumption, which are not fully circular economy approaches; and, on the other, they do not take into consideration the whole complexity of the circular economy and all the possible end-of-life options to close the loop. In other words, some indicators might be mainly focused either on resource efficiency through recycling, without considering other end-of-life options, or on waste recovery, lacking a systemic approach (Geng, Fu, Sarkis, & Xue, 2012; Saidani, Yannou, Leroy, & Cluzel, 2017).

Some authors report that current indicators are not able to link all the systemic levels of the circular economy. In this context, the evaluation of circular economy performance at the nano level becomes crucial in order to "focus on the very core and essence of circular economy, which is the circulation and recirculation of individual products and materials in (open or closed) loops" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 5). However, the literature is barely focused on such indicators (Ghisellini, Cialani, & Ulgiati, 2016).

Given the lack of circularity indicators for products, both academics and organisations (as, for instance, the European Commission and the Ellen MacArthur Foundation) have initiated some projects with the purpose of measuring the circularity of products and the transition towards the circular economy. In this light, the literature counts three major existing tools for measuring product performance in the circular economy: 1) the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (2015a); 2) the Circular Economy Toolkit (CET), developed by Evans and Bocken (n.d.); and 3) the Circular Economy Indicator Prototype (CEIP), developed by Cayzer, Griffiths and Beghetto (2017). The relevance of these tools depends on what it is to be detected: for instance, the MCI is preferable when comparing rapidly the effects of two different materials on circularity performance, while the CET and the CEPI are appropriate when the analysis is more product-centric and lifecycle oriented (Saidani, Yannou, Leroy, & Cluzel, 2017). The following paragraphs present more in depth the three product performance measurement tools.

4.3.2 Material Circularity Indicator

The MCI is presented as a tool for European companies to assess their products and business models performance in the context of the circular economy. This indicator is particularly useful in the design of new products taking circularity into consideration, but it could also be used for both internal reporting and procurement and investment decisions purposes (Ellen MacArthur Foundation; Granta Design; Life, 2015a).

The MCI considers only the technical cycle and the materials generated from non-renewable resources, focusing on the restoration of material flows at the product and company level. The four key principles at its basis are: 1) using feedstock from reused or recycled sources; 2) reusing components or recycling materials after the use of the product; 3) keeping products in use longer (e.g., by reuse/redistribution); 4) making more intensive use of products (e.g., via service or performance models). Therefore, it becomes clear that improvements in the MCI do not necessary lead to improvements in the circularity of the whole system. Specifically, the MCI for a product measures "the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 19).

The MCI is essentially built from the combination of three product characteristics: it firstly considers "the mass of virgin raw material used in manufacture", then "the mass of unrecoverable waste that is attributed to the product", and finally "the utility factor that accounts for the length and intensity of the product's use" (Ellen MacArthur Foundation; Granta Design; Life, 2015a, p. 19). Moreover, complementary risk and impact indicators are considered, in order to provide further insight into the product; precisely, the *complementary risk indicators* include material price variation risk, material supply chain risks, material scarcity and toxicity, while *complementary impact indicators* include energy and water usage and emissions. In practice, the MCI is developed based on an Excel calculation sheet available online for free; moreover, with the aid of a spreadsheet tool, it is possible to calculate product circularity aggregating multi-materials; a guide is also provided regarding the normalisation of the factors for individual products' weight within a general portfolio (e.g., revenues, product mass, and raw materials costs) (Ellen MacArthur Foundation; Granta Design; Life, 2015a).

The MCI presents both strengths and weaknesses. An advantage of the MCI is that it makes it possible to assess material flow potential of products circularity quickly, requiring only a relatively small amount of input data. Indeed, it is an efficient tool for comparing the circularity performance of products with different material combinations (Saidani, Yannou, Leroy, & Cluzel, 2017). Furthermore, the MCI is both general enough and extendable to be computed for products in multiple industrial sectors and thus, serving as a starting point for developing new and advanced product circularity measurement frameworks for more specific industrial sectors.

On the other hand, the MCI is not sufficient by itself to evaluate effective circularity of several products or components. Precisely, given its exclusive focus on the material scale which products and components are composed by, it does not consider multiple crucial aspects which are essential in evaluating the progress towards more circular models. Moreover, it requires specific and detailed knowledge on the bills of materials of the product under evaluation, i.e., the list of the precise type and amount of materials which are used in the production of the parts or components required to build the product. It does not include "modularity, upgradability, connectivity, easy disassembly or design for preventive maintenance of products that are recognized at enablers of an efficient circular economy" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10). Also, the interactions with other components and thus the maximisation of systems rather than components – which is one of the key principles of the circular economy – are not considered. Besides not following a system thinking, the MCI fails to explicitly consider any collaborations between stakeholders, inside the actors' network, or reverse logistics, which are also critical aspects for an effective circular economy. Lastly, the MCI does not clearly promote "closed loops, that is to say, more granular levels of recovery beyond recycling and reuse, such as remanufacturing or refurbishment, assuming that the mass of the product does not change from manufacture to the end of use" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10). Specifically, this implies that, in using a product, some of its parts might be consumed, degraded or lost. Additionally, downcycling, i.e., "the material quality loss in the recycling process" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10) is not considered.

4.3.3 Circular Economy Toolkit

The CET is an assessment tool aimed at identifying potential improvements in product circularity. This tool is freely available online and it consists of a set of 33 questions divided into 7 sub-categories which might be considered similar to the seven stages of a product's lifecycle. It includes seven questions regarding product design, manufacture and distribution; three concerning usage; six concerning product maintenance and repair; three concerning product reuse and redistribution; ten concerning refurbishment and remanufacturing; two concerning product-as-a-service; and two concerning product recycling at end-of-life. It is addressed to both manufacturers, distributors, retailers, purchasers and customers who are asked to answer the questions in a trinary format, i.e., yes-partly-no or high-medium-low. The results are presented in a matrix which relates opportunities and feasibility for product circularity improvements according to the following logic:

> If there is high business opportunity and the product design is well suited, it's rated as a potential 'high opportunity'. If there is little business opportunity and the product design does not aid the service, then it's ranked as a lower opportunity (Evans & Bocken, n.d.).

The main advantage of this tool is that it provides a first overview of improvement opportunities taking into consideration, in the qualitative assessment, both business opportunities and product design. Particularly, it assesses business opportunities with the inclusion of financial viability and market growth potential, and the possible expansions of the following services: maintain/repair, reuse/redistribute, refurbish/remanufacture and products as a service. Moreover, the online platform is easily understandable even for non-experts of the circular economy. The graphical user interface of this tool is indeed very intuitive and user-friendly (Saidani, Yannou, Leroy, & Cluzel, 2017).

However, the CET presents some limitations. For instance, it might be claimed that it is too superficial and that it does not consider and include the whole complexity of the circular economy; in other words, "this toolkit is similar to a qualitative environmental checklist assessment with a trinary-based questionnaire" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10). Moreover, being based on a ternary scale, respondents might be often tempted to select the option in the middle, e.g., partly – medium. Additionally, some questions are considered ambiguous in the sense that they refer to relative and not quantifiable terms, e.g., questions are framed with terms such as *many, few, high* which are too general. Despite its easily understandable interface, in order to properly answer all the questions, it is required a comprehensive knowledge of the product lifecycle. Lastly, the CET provides information about product circularity improvement potential at every stage of the lifecycle, but it lacks further practical recommendations on how to practically implement them (Saidani, Yannou, Leroy, & Cluzel, 2017).

4.3.4 Circular Economy Indicator Prototype

The CEIP aims at evaluating product performance against the circular economy principles during products' design and development phases. The CEIP is a tool available on demand and based on an Excel calculation sheet and built and designed based on the feedback of circular economy experts. It uses a point-based questionnaire which is composed by fifteen weighted questions. The questions are grouped into five lifecycle stages, namely: design or redesign; manufacturing; commercialisation; usage; and end-of-life. Respondents can answer the questions with yes/no answers and, once the questionnaire is completed, a single aggregated score of product circularity performance is provided, as well as a spider diagram displaying circularity performance across different parts of the lifecycle.

The strengths of the CEIP are its ease of use, simplicity, and speed in product circularity evaluation. Moreover, it is particularly effective in showing how spread the circular economy principles are among industrial practices.

However, its interpretation through a single score hides the true circular economy complexity and the binary scoring system used for some question could be quite reductive. Moreover, the authors of the CEIP acknowledge that:

> The reliability of the questionnaire is based on the case study specific context, meaning that the 15 questions are mainly focused on the manufacturing and end-of-life stages of the product lifecycle, they therefore neglect certainly other crucial aspects of the circular economy (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10),

such as "modularity, design for disassembly, upgradability, use of new technology or connected devices: for instance, sensors to enable product traceability" (Saidani, Yannou, Leroy, & Cluzel, 2017, p. 10). Lastly, it requires access to specific product information to complete the questions (Saidani, Yannou, Leroy, & Cluzel, 2017).

Tools Characteristics	Circular Economy Toolkit (CET)	Material Circular Indicator (MCI)	Circular Economy Indicator Prototype (CEIP)
Description	It is an assessment tool to identify potential improvement of products' circularity.	It aims at helping companies to measure their transition towards a circular economy.	The CEIP aims at evaluating product performance in the context of circular economy.
Platform Support	Dynamic Webpage	Excel Spreadsheet	Excel Spreadsheet
Inputs	33 trinary-based questions divided into 7 sub-categories related to lifecycle stages.	Different percentages (reused, recycling) about material origin (feedstock) and destination (after use).	15 weighted questions divided into 5 lifecycle stages.
Outputs	Qualitative: Improvement potential at 3 level (high, medium, low) for every of the 7 sub-categories.	Quantitative: The MCI, single score, gives a value between 0 and 1 where higher values indicate a higher circularity.	Quantitative: The CEIP score (%) and a radar diagram showing aggregated score for each lifecycle stage.

Table 6 Tools description, characteristics and operating mode. Source: Saidani, Yannou, Leroy, and Cluzel, (2017, p. 7)

4.4 Limitations and Delimitations

4.4.1 Beyond the Technical Cycle

This study aims to develop an instrument that measures the degree of product circularity, to be diffusely used by the academia in order to broaden the existing research on the circular economy, its implementation and implications. Despite attempting to create a rather general instrument to ensure a wide applicability, the core characteristics of the circular economy concept itself, as well as the instrument development process undertaken in the study, led to several limitations which restricted the scope of the research. Such limitations, described below, may encourage further studies so that the instrument can be refined and improved.

Looking at the butterfly diagram developed by the Ellen MacArthur Foundation (2013a), it can be noticed how the circular economy model differentiates between biological and technical closed loops. The two cycles are fundamentally different, mainly in that they require distinct types of strategies in order to be realized: As described, technical cycles relate to the supply chain of products made of technical materials, and their circular economy model should leverage the four circularity loops of maintenance, reuse, remanufacture and recycle – thus leaning on specific product design and business model strategies aimed to slow and close resource loops. On the other hand, biological cycles – characterized instead by biological nutrients – focus on the restoration of materials, therefore operating through cascading, composting and farming activities. It seems clear how this distinction prevents the creation of a general instrument that can measure the degree of product circularity in both cycles, as the two types of products would be characterized by different types of materials and resources, as well as strategies and operations. As a result, the instrument hereto developed is meant to be applied exclusively to technical cycles – as it is not related to biological products and strategies and thus it cannot be representative of biological cycles.

If, on the one hand, the instrument is constrained by its applicability limited to industries characterised by technical cycles, on the other hand, such instrument may be biased by the fact that it does not differentiate among industries *within* these technical cycles. As a matter of fact, in order to create an instrument that can measure the degree of product circularity across several industries, the research focuses on characteristics of product circularity which can describe products belonging to several industries, indiscriminately. Therefore, the instrument does not take into consideration the specific characteristics defining each industry, which differentiate products and, accordingly, their product design and business models. Such differences among industries may have an impact on how the degree of circularity of a product can be assessed. As a consequence, the instrument's effectiveness in reliably measuring the degree of product circularity would highly be improved if adapted to the specific characteristics of different industries.

4.4.2 Beyond Product Circularity

The idea underlying this study is to develop an instrument to measure the circular economy at its inner level of implementation, namely the nano level, taking into analysis several circularity factors related to product design, business model, technological revolution, materials management and promotion and customer involvement – identified in the literature as the catalysts of the circular economy at the product level. However, the product's manufacturing process, an additional fundamental factor to be considered when assessing circularity, remains beyond the scope of this study. Such choice stems from the fact that the manufacturing process represents a complex stage of a product's development, which can hardly be associated with product design and business model decisions happening at the early stages of product creation. With the aim of keeping the instrument rather simple, we figured that it would be best to assess circularity in the manufacturing process separately.

While the present research is restricted to those aspects of the circular economy which attain to products, the broader objective of the study is to encourage research on the circular economy at large. A better understanding of the circular economy could enhance the implementation of an industrial model which is, potentially, a sustainable alternative to the linear model. To this end, the circular economy should be further researched from a supply chain perspective – hence, the analysis of product circularity is necessary but not sufficient. As described in the *Theoretical Framework*, the circular economy requires collaboration among the actors along the supply chain, suggesting the existence of additional catalysts of the circular economy to the ones characterising products, specifically. As a matter of fact, the instrument developed in this study, in addition to a detailed analysis of products' manufacturing processes, should be complemented with the assessment of the circular economy at the micro and meso level, in order to develop a comprehensive understanding of the circular supply chain and its determinants. More specifically, the *Theoretical Framework* described how the implementation of the circular economy goes beyond the individual firm, and how taking a system perspective is necessary. When analysing the product supply chain as a whole, additional factors to be considered in measuring the circular economy emerge – including, but not limited to, questions on whether suppliers and/or retailers have circular activities implemented, as for instance if they collect products at their end-of-life.

4.4.3 Beyond the Circular Economy

In addition to closing the loop on product system material flows, additional factors should be considered during a product's development, and combining the circularity assessment with an evaluation of several other indicators is necessary. The Ellen MacArthur Foundation (2015a) defined these indicators as *complementary* and classified them as *complementary risk indicators* and *complementary impact indicators*. As previously described, the first class includes all indicators which could provide insights into potential risks of implementing a circular economy model in relation to business priorities, e.g., risks related to materials' price variation, supply chain risks, materials' scarcity and toxicity. The second class includes those indicators which could provide insights into the consequential impacts of changing the level of material circularity, such as energy usage, CO_2 emissions and water footprints. Existing indicators are available to measure these risk and impact factors, and are described in detail by the Ellen MacArthur Foundation (2015a): their evaluation should necessarily be complemented with the analysis of product circularity, in order to obtain an overall effective circular economy assessment.

5. Research Design and Methodology

5.1 Research Approach

Depending on the aim of the study, its research questions, the research strategies and methods, the literature suggests the adoption of three main research approaches: quantitative, qualitative and mixed methods (Creswell, 2014). Qualitative studies are characterised by inductive reasoning, focused on theory building. In other words, the researchers aim at exploring and understanding a problem starting from the collection and interpretation of the data, going first through an empirical level and afterwards through a conceptual-abstract level (Creswell, 2014). Data are non-numerical (Saunders, Lewis, & Thornhill, 2009) and they are collected through *observing a setting* and usually using open-ended questions during interviews (Creswell, 2014).

On the other hand, a quantitative research presents a more deductive reasoning, where the researchers' aim is that of testing an objective theory and exploring the relationship among variables. Such variables can be measured and data – which are numerical, usually coming from closed-ended questions – can be analysed through statistical inference (Saunders, Lewis, & Thornhill, 2009). Researchers must defend their findings against biases and be able to generalise and replicate them (Creswell, 2014).

However, these definitions are not rigid and are not one the opposite of the other; instead, they must be considered as the two terminations of a segment, where the research can lay anywhere in between. A peculiar case is identified when the research lays exactly in the middle of this imaginary segment, between the qualitative and quantitative extremes. This kind of research is said to be a mixed methods research, which incorporates aspects coming from both approaches (Creswell, 2014).

The concept of mixed methods research is relatively new in the methodology field, and a first comprehensive review on this approach is dated back to 2003 with the publication of the *Handbook of Mixed Methods in the Social* and *Behaviour Sciences* (Tashakkori & Teddlie, 2003). A more recent work on mixed methods research is presented by Johnson, Onwuegbuzie, and Turner (2007). Besides providing a definition of the field, the authors discuss its criteria of demarcation. The proposed definition of mixed methods research is based on the analysis of nineteen definitions coming from leaders in the area of mixed methods research, and states the following:

> Mixed methods research is the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration. […] A mixed methods study would involve mixing within a single study; a mixed method program would involve mixing within a program of research and the mixing might occur across a closely related set of studies (Johnson, Onwuegbuzie, & Turner, 2007, p. 123).

As a matter of fact, mixed methods research has gained increasing importance as a research practice – especially among the social science disciplines – to the point that Johnson, Onwuegbuzie, and Turner (2007) positioned it as the third major research approach or research paradigm next to qualitative and quantitative research (Johnson & Onwuegbuzie, 2004).

The previous paragraph briefly anticipated how research approaches can be pictured as an imaginary segment, or a *continuum*, in which the ends are defined as *pure* qualitative research approach – on the left side – and *pure* quantitative research approach – on the right. The portion of the segment that goes from its ends (but excluding the area around the poles) toward the middle of the segment is where the research is defined, generally speaking, mixed methods research. The point in the very middle of this *continuum* is referred to as *pure* mixed methods approach. Specifically, the area around such point is where the two approaches gain an *equal status* (Johnson, Onwuegbuzie, & Turner, 2007, p. 123). On the other hand, the left side of the segment, going from the centre towards the left-side pole, represents the qualitative mixed and qualitative dominant research; conversely, the right side of the segment, going from the centre towards the right-side pole, represents the quantitative mixed and quantitative dominant research.

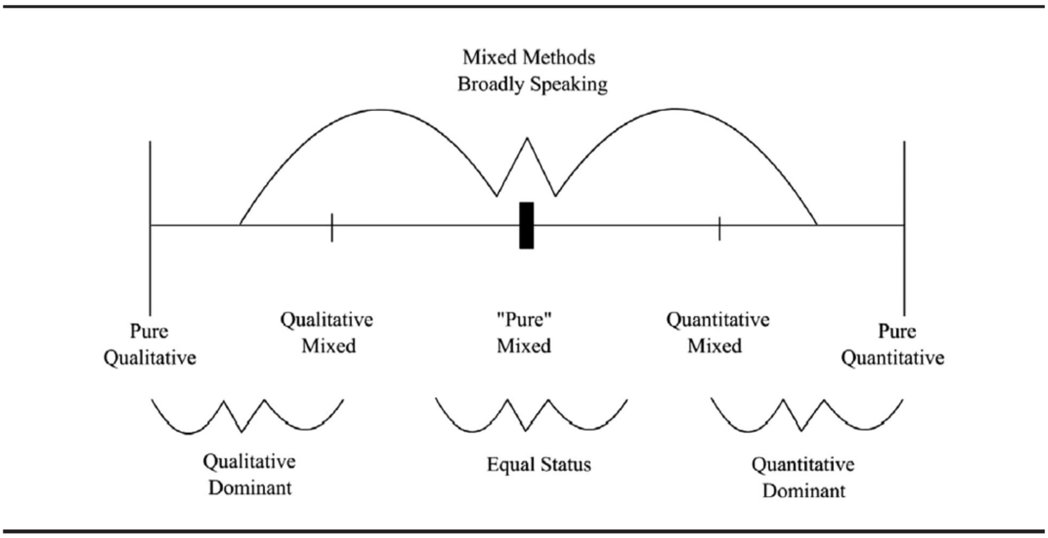

Figure 4 Graphic of the Three Major Research Paradigms, Including Subtypes of Mixed Methods Research. Source: Johnson, Onwuegbuzie, and Turner (2007, p. 124)

More in depth,

> Qualitative dominant mixed methods research is the type of mixed research in which one relies on a qualitative, constructivist-poststructuralist-critical view of the research process, while concurrently recognizing that the addition of quantitative data and approaches are likely to benefit most research projects (Johnson, Onwuegbuzie, & Turner, 2007, p. 124)

while,

> Quantitative dominant mixed methods research is the type of mixed research in which one relies on a quantitative, postpositivist view of the research process, while concurrently recognizing that the addition of qualitative data and approaches are likely to benefit most research projects (Johnson, Onwuegbuzie, & Turner, 2007, p. 124).

This mixing of data, being them both open-ended data in the case of qualitative and closed-ended data in the case of quantitative research, makes it possible to join the strengths and to minimise the limitations of the two approaches, thus providing a deeper understanding of the research problem (Creswell, 2014). Specifically, the purposes of conducting mixed methods research are twofold: breadth and/or corroboration. Breadth entails a fuller picture and deeper understanding and enhances description and understanding. On the other side, corroboration refers to the triangulation of the findings (Johnson, Onwuegbuzie, & Turner, 2007). Other authors include in their definition of mixed methods approach that it (a) "validates and explicate findings from another approach and produces more comprehensive, internally consistent, and valid findings"; (b) "provides more elaborated understanding and greater confidence in conclusions"; (c) "handles threats to validity and gains a fuller and deeper understanding" (Johnson, Onwuegbuzie, & Turner, 2007, p. 122).

The literature finds that a mixed methods approach is preferable when developing a measurement instrument (Creswell, 2014; Johnson, Onwuegbuzie, & Turner, 2007). Hence, given the aim of this study and according to the research question, among the three possible research approaches – qualitative, quantitative or mixed methods – this research adopts a mixed methods approach.

5.2 Research Design

The next step, after defining a mixed methods research approach as preferable for this kind of study, is to clarify which mixed methods design is to be implemented when addressing the research question. Research design represents a model for data collection, analysis, interpretation and report in research studies (Creswell & Plano Clark, 2007), and it is defined as the *logical structure* of the inquiry. Indeed, the research design guides the method decision in order to collect evidences which are able to respond to the research question in the least possible ambiguous and most possible convincing way (Creswell, 2014).

Within the mixed methods research, there are at least forty different types of design which have been classified in twelve groups. A more comprehensive and parsimonious classification takes into consideration both the similarities among some types of designs and their differences compared to others, leading to the identification of four major types of mixed methods design: 1) triangulation design; 2) embedded design; 3) explanatory design; 4) exploratory design (Johnson, Onwuegbuzie, & Turner, 2007).

Research designs differ in several aspects. First, mixed methods designs are classified as either parallel or sequential – or, in other words, characterized by either one or two phases. In the first case, the quantitative and qualitative research take place at the same stage of the study – either in data collection or during the interpretation of the results – while, in the latter, one phase is followed by the other (Saunders, Lewis, & Thornhill, 2009). Another crucial classification regards the way in which the quantitative and qualitative researches are merged during the study, i.e., whether the design is either explanatory or exploratory. On the one hand, explanatory methods first perform quantitative research and then findings are analysed through qualitative research. Conversely, exploratory methods perform the reverse sequence (Creswell, 2014).

Triangulation design "generally involves the concurrent, but separate, collection and analysis of quantitative and qualitative data so that the researcher may best understand the research problem" (Creswell, 2006, p. 64). This kind of research allows to combine the strengths of the two data sets: on the one side, the large sample size and the trend and generalisation of quantitative data; on the other, a more detailed and in-depth information collectable through qualitative data. The procedure of this design is one-phase. Indeed, the qualitative and quantitative methods are implemented at the same time and with equal weight, while the results coming from the different data sets are usually merged together in the interpretation phase or integrated during the analysis. Some variants of the triangulation design are 1) the convergence model; 2) the data transformation model; 3) the validating quantitative data model and 4) the multilevel model (Creswell, 2006).

Embedded design is a type of mixed methods design "in which one data set provides a supportive, secondary role in a study based primarily on the other data type" (Creswell, 2006, p. 67). Specifically, one type of data is embedded with the methodology typical of the other type of data. For instance, quantitative data might be embedded with qualitative methodology. The experimental model and the correlational model are the variants of this design (Creswell, 2006).

Explanatory design is a two-phase mixed method design where "qualitative data helps explain or build upon initial quantitative results" (Creswell, 2006, p. 71). Indeed, it includes a first phase designated to the collection and analysis of quantitative data followed by a second phase where qualitative data are collected and analysed in relation to the results of the first quantitative phase. This design counts two variants: the follow-up explanations model and the participant selection model. The key differences between these variants are, on one side, the connection of the two phases and, on the other, the relative emphasis given to them (Creswell, 2006).

Lastly, exploratory design is a two-phase design where "the results of the first method (qualitative) can help develop or inform the second method (quantitative)" (Creswell, 2006, p. 75). Exploratory sequential mixed methods are first characterised by a qualitative phase. Then, once the data gathered during this phase are analysed, they are used in the quantitative phase (Creswell, 2014). More specifically, "the qualitative phase may be used to build an instrument that best fits the sample under study, to identify appropriate instruments to use in the follow-up quantitative phase, or to specify variables that need to go into a follow-up quantitative study" (Creswell, 2014, p. 44). Its variants are twofold: instrument development model and taxonomy development model. The instrument development model is used:

> To develop and implement a quantitative instrument based on qualitative findings. In this design, the researcher first qualitatively explores the research topic with a few participants. The qualitative findings then guide the development of items and scales for a quantitative survey instrument. In the second data collection phase, the researcher implements and validates this instrument quantitatively. In this design, the qualitative and quantitative methods are connected through the development of the instrument items (Creswell, 2006, p. 77).

On the other hand, the taxonomy model is used when:

> A researcher formulates quantitative research questions or hypotheses are formulated based on qualitative findings and proceeds to conduct a quantitative study to answer the questions. In addition, a researcher may identify emergent categories from the qualitative data and then use the quantitative phase to examine the prevalence of these categories within different samples or use taxonomy affiliation as a basis for identifying comparison groups (Creswell, 2006, p. 78).

Overall, as the purpose of this work is to develop an instrument, the present research uses an exploratory sequential mixed methods design, as defined by Creswell (2006) and Creswell (2014) and summarised in *Figure 5*.

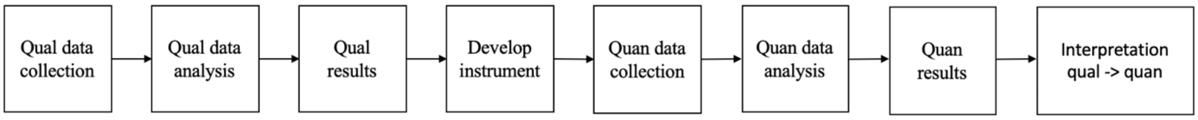

Figure 5 Exploratory design: Instrument Development Model. Source: Creswell (2006, p. 76)

5.3 Methodology

5.3.1 Instrument Development Process

In order to develop a sound measurement of the degree of product circularity, a three-stage process was carried out, following Moore and Benbasat (1991)'s instrument development model. The three stages of the process are (1) Item Creation – referred to creating a pool of items to match each construct definition and ensure content validity; (2) Scale Development – referred to sorting items into construct categories and examining inter-rater reliabilities, in order to ensure construct validity; and (3) Instrument Testing – referred to administering the survey instrument to a pilot sample to check reliability of the construct categories (Moore & Benbasat, 1991). Throughout the three stages of the process, it is crucial to ensure *validity*, *reliability* and *parsimony* of the instrument. As defined by Wieland, Durach, Kembro and Treiblmaier (2017), reliability refers to "the consistency of measurement" (Bryman & Bell, 2015, p. 169), validity is "the issue of whether or not an indicator (or set of indicators) that is devised to gauge a concept really measures that concept" (Bryman & Bell, 2015, p. 170), and parsimony is defined as "the principle that measurement is based on the least amount of information necessary (e.g. number of items, text per item)" (Wieland, Durach, Kembro, & Treiblmaier, 2017, p. 322).

Of the three stages described above, the first two – Item Creation and Scale Development – were performed and completed in this study, and content and construct validity were ensured throughout the process. The final result of the study is a scale instrument consisting of 32 items, which has to be further improved and refined through the final stage of the process, the Instrument Testing, in order to assess the reliability of the scale and to further ensure its validity.

5.3.1.1 Item Creation

The first stage of the instrument development process implemented in this research began with defining the constructs and variables to be measured. The circular economy, specifically at the product level, is conceptualized as a formative second order construct, in which the latent variable is observed through observable items, which are determinants of the construct itself (Diamantopoulos, Riefler, & Roth, 2008). This stage can be further divided into two steps: the domain identification, during which the constructs are identified and defined, and consequently the development of the actual initial pool of items.

Domain Identification

The existing body of literature on the circular economy was reviewed with the aim of identifying the determinants of circularity at the nano level. The rationale behind adopting a formative second order model lies in the acknowledgment that the main requirement to achieve a higher level of product circularity is to implement a systemic change in the circular economy determinants – defined in the literature as the catalysts, or enablers, of product circularity. Five main constructs were identified in the literature as the catalysts of product circularity:

- *Product Design*: Design has been recognised in the literature as a catalyst to move away from the *take-make-dispose* paradigm and achieve circular economy (Moreno, De los Rios, Rowe, & Charnley, 2016). The importance of product design's role within the circular economy stems from the recognition that a business built around long-life products and recovered resources necessitates products that support that strategy, preferably by intention and design (den Hollander, Bakker, & Hultink, 2017). As a matter of fact, it is fundamental to integrate circularity at an early stage, because product design – with the commitment of resources, infrastructures, and activities involved in the process – defines a product's specifications in a way that will be difficult to change afterwards (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). Without a systemic change in the way products are designed, the potential of a circular economy cannot be achieved (Moreno, De los Rios, Rowe, & Charnley, 2016). As stated by Moreno, De los Rios, Rowe and Charnley (2016), "Design for a circular economy has to consider different design strategies for closed loop systems as a pivotal point for its success" (Moreno, De los Rios, Rowe, & Charnley, 2016, p. 2).
- *Business Model*: The design for a circular economy needs to be applied in conjunction with business models that allow the repeated capture of economic value over time. As described in the *Conceptual Framework*, the business model, representing the second catalyst to achieve product circularity, is characterized by (1) the value proposition, referred to the product/service offering; (2) the value creation and delivery, i.e., how the

value is provided; and (3) the value capture, specifically referred to how the company makes money (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). Similarly to product design, the creation and implementation of innovative circular business models are essential, so that the potential of a circular economy can be achieved.

- *Technological Revolution*: The Ellen MacArthur Foundation (2016b) has identified new technologies, and specifically the Internet of Things, as an enabler of the circular economy. Particularly at the product level, the ability of the 21st century's technological revolution, of collecting and storing an enormous amount of information and data, has the potential of creating new value opportunities, by facilitating the implementation of circular practices (Ellen MacArthur Foundation, 2016b).
- *Materials Management*: as mentioned in the *Conceptual Framework*, the circular economy revolves around a paradigm shift in the redesign of the flow of materials and a systemic change in the utilization of resources. As defined by the United States Environmental Protection Agency (USEPA, 2009), "materials management is an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated environmental impacts" (USEPA, 2009, p. 11).
- *Promotion and Customer Involvement*: Involving customers is fundamental for companies willing to achieve a higher degree of product circularity. Customers can be involved in the implementation of circular practices in various ways. Specifically, companies can make visible to their customers their compliance to the circular economy principles, through promotion activities. Moreover, companies can also facilitate customer responsibility and the relationship customers themselves have with circular practices, by providing information with the product on, for instance, how to dispose of it, or encouraging reuse and recycle.

Pool of Items Development

After identifying the five constructs defined above, a pool of items was, thus, created to match each construct definition. The aim of this step is to ensure content validity of the measurement items, and therefore that the instrument covers all the items to reflect the definition of the circular economy (Moore & Benbasat, 1991). After an initial pool of items was created by analysing the existing literature on the circular economy, it was first evaluated by two circular economy experts and then modified to eliminate all items considered too narrow in focus, too ambiguous or redundant, resulting in a list of 106 items, formulated as statements referred to a specific existing company's product.

5.3.1.2 Scale Development

The second stage of the instrument development process was carried out using the Q-Sort method, which is an iterative process performed in order to assess construct validity, through the analysis of the degree of agreement between judges (Nahm, Solís-Galván, Rao, & Ragun-Nathan, 2002). Following Moore and Benbasat (1991)'s approach, the procedure consisted of four sorting rounds performed with the twofold aim of ensuring construct validity and identifying items which still may have seemed ambiguous.

Sorting Procedures

A total of sixteen judges – four per each round – were selected from four distinct areas of expertise in order to guarantee a certain level of diversity in the panel of experts. The judges were selected as follows:

- Five sustainability and/or circular economy experts (one Postdoc and one PhD fellow from Copenhagen Business School, one Professor and one PhD fellow from Aalborg University, and one PhD candidate from the University of South Australia);
- Four supply chain management experts (one Associate Professor, one Assistant Professor, one Postdoc and one PhD fellow from Copenhagen Business School);
- Four digitalization and innovation experts (one Professor Emeritus, one Associate Professor and two Assistant Professors from Copenhagen Business School); and
- Three marketing and/or research methods experts (one Associate Professor, one Assistant Professor and one PhD student from Copenhagen Business School).

The judges were invited to individual meetings, during which they were asked to sort the selected items into construct categories, according to the following logic:

- During the first and third rounds, the judges were asked to sort the items into construct categories providing their own label categories, and they were advised to create an *I Don't Know* category for those items which resulted too ambiguous. Moreover, judges were asked to indicate the clarity of the statements on a five-point scale – from *Not*

Clear to *Perfectly Clear* – and provide a comment for those items characterized by a low clarity scale;

- During the second and fourth rounds, the judges were asked to sort the items into the pre-defined construct categories, namely *Product Design*, *Business Model*, *Innovation*, *Materials Management*, *Customer Interaction* and *I Don't Know* in the second round; and *Product Design*, *Business Model*, *Technological Revolution*, *Materials Management*, *Promotion and Customer Involvement* and *I Don't Know* in the fourth round. Moreover, they were asked to indicate the same clarity scale as in the 1st and 3rd round, and to give each item a five-point representativeness scale, indicating the degree to which the items matched the construct they associated them with.

Inter-Rater Reliabilities

After each sorting round, two different measurements were used to assess inter-rater reliabilities (the reliability of the sorting conducted by the judges): Cohen's Kappa and Item Placement Ratio (Moore & Benbasat, 1991). Cohen's Kappa (Cohen, 1960) was computed in STATA for each pair of judges to measure their level of agreement in categorizing items, and subsequently an overall level of agreement was assessed by computing the average Cohen's Kappa from the six pairs. Although no general agreement exists with respect to required scores of Cohen's Kappa coefficients, several studies consider scores greater than 0.65 to be acceptable (Moore & Benbasat, 1991). Landis and Koch (1977) developed the following guideline to interpret Cohen's Kappa coefficients:

Kappa Statistic	*Strength of Agreement*
< 0.00	*Poor*
0.00 – 0.20	*Slight*
0.21 – 0.40	*Fair*
0.41 – 0.60	*Moderate*
0.61 – 0.80	*Substantial*
0.81 – 1.00	*Almost Perfect*

Table 7 Interpretation of Cohen's Kappa Coefficients. Source: Landis and Koch (1977)

The Item Placement Ratio, a measure developed by Moore and Benbasat (1991), was computed to measure both the reliability of the classification scheme and the validity of the items, by analysing how many items were placed by the four judges in each round within the target constructs. As described by the authors, the Item Placement Ratio is a measurement of the overall frequency with which all judges placed the items within the target theoretical constructs. A high percentage of items placed in the target constructs indicates a high degree of agreement among the judges and a high degree of construct validity. The Item Placement Ratio is not characterized by a specific scale to determine acceptable levels of placement. Nevertheless, the matrix is a good indicator to highlight potential problem areas. (Moore & Benbasat, 1991).

5.3.1.3 Instrument Testing

The third and final stage of the instrument development process consists of a pilot test and a field test of the overall instrument, conducted with the twofold aim of assessing the reliability of the constructs and further assessing their validity. As mentioned at the beginning of this section, the Instrument Testing stage remains beyond the scope of this study. However, it is described below as a guideline for further research aimed to complete the instrument development process.

The pilot test is conducted by administering a survey to a relatively small sample of companies. The survey is created by randomly ordering the 32 items remaining in the pool after the Scale Development stage, into a common group of statements, and asking respondents to indicate their level of agreement with each statement on a seven-point Likert scale – from *Strongly Agree* to *Strongly Disagree*. The choice of a seven-point – over a five-point – Likert scale is motivated by several studies suggesting that reliability is optimized with seven response categories (Colman, Norris, & Preston, 1977). The participating companies should be selected according to their industry, so that the survey is administered exclusively to firms in technical – and not biological – cycles.

Reliability Assessment

In order to assess the reliability of the constructs, the six measures of reliability discussed by Guttman (1945) are used. Following Moore and Benbasat (1991)'s approach, Cronbach's ALPHA (Cronbach, 1970) is highlighted in the analysis, with a target level of minimum reliability set in the 0.70 to 0.80 range. The item-item correlations within each scale, the item-scale correlations, the effects on ALPHA if the item are deleted, and the item standard deviation scores are used to determine which items are candidates for deletion. Low item-item and item-scale correlations would raise ALPHA if deleted, therefore such items are candidates for elimination. Moreover, a low variance indicates that items would have low explanatory power in any model, making those items also candidates for elimination (Moore & Benbasat, 1991).

Factor Analysis

Both exploratory and confirmatory factor analyses are performed as a further assessment of construct validity. As described by Moore and Benbasat (1991), because in traditional factor analysis results are "indeterminate" due to the fact that factor loadings can be rotated in numerous ways, "data analysis where possible ought to be grounded in strong a priori notions" (Moore & Benbasat, 1991, p. 206). The authors also highlight how this idea fits the approach of this type of research, where constructs categories are identified and defined prior to the development of the initial pool of items, and such constructs are based on a substantial body of prior research. Moreover, this is also in line with several prescriptions that items should fit the constructs' conceptual meaning, in order to ensure construct validity (Moore & Benbasat, 1991).

Principal Components analysis is conducted to identify the number of factors to be maintained, by looking at both the eigenvalues, which should be greater than 1.0, and the scree plot break. This analysis also suggests how much variance in the model is explained by the factors, and if the items are fairly clean (by looking at their factor loadings). Next, the rotated factor matrix is examined for items which do not load strongly on any factors (<0.40) or are too complex (load highly or relatively equally on more than one factor), to identify items candidate for elimination. Results from the exploratory factor analysis should be further analysed by conducting a confirmatory factor analysis. In this case, Moore and Benbasat (1991) suggest that loadings exceeding 0.45 are considered fair, greater than 0.55 good and greater than 0.71 excellent.

5.3.2 Methodology Limitations

The present study was performed following Moore and Benbasat (1991)'s approach rather strictly. Nonetheless, several limitations – due almost entirely to time constraints – may undermine the accuracy of the conducted research.

Concerning the Scale Development stage, it was mentioned that the sixteen judges who participated in the sorting rounds were selected from four different areas of expertise, in order to ensure a fair level of diversity in the panel of experts. The initial aim of this choice was to divide the sixteen judges into the four sorting rounds so that each round would involve one judge from each area of expertise. More specifically, each panel of judges would consist of one expert in sustainability and/or circular economy, one expert in supply chain management, one expert in digitalization and innovation, and one expert in marketing and/or research methods. Unfortunately, the sorting procedures were performed in a pre-determined and not extendable period of time, thus it resulted impracticable – due to ours and the judges' availability – to divide the sixteen judges into four rounds according to the above-described logic. Moreover, three instead of four marketing and/or research methods experts participated in the study, thus the last marketing and/or research methods expert was replaced by a sustainability and/or circular economy expert. As a result, the sixteen judges were divided into the four rounds as follows:

- In the first round, the judges who participated in the sorting procedure were one marketing and/or research methods expert, one sustainability and/or circular economy expert and two supply chain management experts;
- In the second round, the judges who participated in the sorting procedure were three digitalization and innovation experts and one supply chain management expert;
- In the third round, the judges who participated in the sorting procedure were one digitalization and innovation expert, two sustainability and/or circular economy experts and one supply chain management expert;
- In the fourth round, the judges who participated in the sorting procedure were two marketing and/or research methods experts and two sustainability and/or circular economy experts.

Moreover, as the final Instrument Testing stage of the process was beyond the scope of this research, the instrument scale consisting of 32 items hereto developed cannot be considered complete, and a pilot test – accompanied, eventually, by a final field test – should be performed to finalize the instrument.

6. Results and Discussion

6.1 Analysis of the Results

6.1.1 First Sorting Round

The judges selected for the first sorting round were invited to four individual meetings which lasted, on average, 57 minutes. During these meetings, the four judges were presented with an initial pool of items consisting of 106 statements, and they were asked to sort the items into several construct categories they had to identify on their own. Each judge identified a different number of construct categories: more specifically, the four judges identified, respectively, seven, twenty, twelve and eleven different construct categories. Despite the fact that the judges labelled the construct categories in different ways, the definitions they provided for each category presented some similarities, both to the other judges' categories and to the five pre-defined constructs. This analysis was essential to gather a first idea of construct validity; in other words, as stated by Moore and Benbasat (1991), if several judges are able to define their categories in a way that matches the definitions of the pre-defined constructs, then the confidence in construct validity increases. *Table 8* shows the judges' labels for the construct categories they identified, matched with the pre-defined constructs.

		Judges			
		A	B	C	D
Constructs	Product Design	Product design and manufacturing to increase circularity Product design to alter/change usage	Modularity of components Designed for durability	Product design	Product design Product characteristics
	Business Model	Product usage approach to increase circularity	Leasing	Business model	
	Innovation	Use of IoT to enhance product performance and usability	Sensors		IT and circularity
	Materials Management		Biological materials Waste reduction Avoiding materials Taking back for recycling	Material input Waste management	
	Customer Interaction	Incentive to customers to consume sustainably Communication to customers to increase circularity	Marketing to promote circularity Promoting repairability Promoting non-consumerism Product info regarding recycling	Customer interaction Promoting sustainability	Direct customer Information circularity promotion
	NA	Recycling and after-sales procedures to	Responsibility in other product categories Use of green energy Disposal of products Packaging recycling Reusability of components in the CO2 avoidance Use of standards Reusability of product	Product use Manufacturing sustainability Packaging design Sustainable logistics Circular process Product maintenance	Non-circularity Packaging Circularity process Circularity strategy Production strategy Production process

Table 8 Judges' Labels First Sorting Round

The table was created in a way that the judges' constructs categories which could be associated with the pre-defined constructs or interpreted as a subcategory, were considered as matching the pre-defined constructs. For instance, the category *material input* identified by one of the judges, was considered as fitting the Materials Management construct, and the category *modularity of components* was considered as a subcategory of the Product Design construct. All the judges' categories which could not be matched with any pre-defined construct were considered as *non-applicable* (NA). For instance, the category *use of standards* identified by one of the judges was considered as NA because it could not fit any of our construct definitions.

Table 8 is an indication of which of our construct categories the four judges identified based on the initial pool of 106 items. The first judge identified seven categories, two of them corresponding to Product Design, one equivalent to Business Model, one to Innovation, and two to Customer Interaction, with only one NA category. However, the first judge did not identify any category associated with Materials Management. The second judge identified twenty different categories. Two of them were associated with Product Design, one with Business Model, one with Innovation, four with Materials Management and four with Customer Interaction; the remaining eight categories were assigned to the NA category. Among the twelve categories identified by the third judge, one was associated with Product Design, one with Business Model, none with Innovation, two with Materials Management and two with Customer Interaction; six categories were placed in the NA category. The fourth judge identified eleven categories, two of which fitted Product Design, one Innovation and two Customer Interaction; no categories were identified by the judge for Business Model and for Materials Management, and six categories were placed in the NA category. Finally, three judges out of four added an 'I do not know' category for those items they were not able to include in any other category. However, only a small number of items was placed by the judges in this category.

In sum, all of the four judges identified either a Product Design category or Product Design subcategories, and they all identified categories related to Customer Interaction. Conversely, one of the judges did not identify a Business Model category, one did not identify Innovation and two did not identify Materials Management. Moreover, a total of 21 construct categories out of the total number of 50 construct categories was placed in the NA category. Overall, this analysis suggests that construct validity of our construct categories must be improved.

Inter-Rater Reliabilities

The inter-judge raw agreement scores averaged 47.96%, while Cohen's Kappa scores averaged 0.2851 and the initial overall Item Placement Ratio was 38.44%. The average agreement score was not high but still quite good, considering that this was the first round. Specifically, the lowest score registered among the pairs of judges was 36.79%, while the highest reached 58.49%. However, for all the pairs of judges, Cohen's Kappa scores never reached the 0.65

acceptable level, as they averaged much below this threshold. Indeed, the lowest score registered is 0.1775 and the highest is 0.4051. *Tables 9* and *10* show the agreement scores for each pair of judges, where the four judges are labelled, respectively, A, B, C and D.

	A	B	C	D
A		41.51%	36.79%	51.89%
B			50.00%	58.49%
C				49.06%
D				
Average				47.96%

Table 9 Raw Agreement Scores First Sorting Round

	A	B	C	D
A		0.2592	0.1775	0.3319
B			0.2871	0.4051
C				0.2499
D				
Average				0.2851

Table 10 Cohen's Kappa Scores First Sorting Round

The overall hit ratio registered a relatively low percentage (38.44%). This might be justified by the fact that a high number of items was assigned to the NA category due to the fact that the judges identified a higher number of categories than the five construct categories. For instance, 62% and 48% of the items intended as measuring the Materials Management and Business Model constructs, respectively, were instead assigned to the NA category. Lower percentages were registered for the other constructs, but still 43% of Product Design items, 31% of Innovation items and 24% of Customer Interaction items resulted in the NA category.

The diagonal of the item placement matrix, shown in *Table 11*, represents the number of items that the judges placed within the target constructs. In this round, the highest hit ratio is the one for Customer Interaction, with 75% of the items placed within the target construct. Innovation registered 56.25% of hits, followed by Product Design, with 41.4% of hits. The Item Placement Ratio for the Business Model and Materials Management categories is very low, registering 17.86% and 19.23% of hits, respectively. This means that out of all the items intended to fall within the Business Model category, only 17.86% of them were placed by the judges within the target construct, while the rest was assigned to other categories. According to the same logic, only 19.23% of the items intended to be in the Materials Management category were placed within the target construct by the four judges.

As well as the diagonal, it is also worth noticing the off diagonals of the matrix, which might show the presence of off-target clusters. In this round, the judges assigned many more items to the Product Design construct than expected. For instance, many items intended as Materials Management were assigned to Product Design. This may be due to the fact that two judges had not identified Materials Management as a separate category and assigned many of those items to Product Design instead, also suggesting that these two categories may overlap. Similarly, many items intended as Business Model were assigned to the Product Design category instead.

	Actual Categories							
Target Categories	Product Design	Business Model	Innovation	Materials Management	Customer Interaction	N/A	Tot	TGT
Product Design	53	5		7	8	55	128	41.41%
Business Model	15	15		7	7	40	84	17.86%
Innovation	4		18			10	32	56.25%
Materials Management	19			20		65	104	19.23%
Customer Interaction	1				57	18	76	75.00%
Total Item Placements	*424*							
Hits	*163*							
Overall Hit Ratio	38.44%							

Table 11 Item Placement Ratio First Sorting Round

Changes Performed after the First Round

After the first sorting round, several changes were made to the items. The changes made to the items were determined by the judges' labels for their construct categories, the clarity scale given by the judges to each item, and the judges' comments about the clarity of the items.

Concerning the judges' labels for the construct categories, judges systematically assigned a certain number of items to categories related to the manufacturing process, the production process, and the circular process. As the instrument developed in this study aims to measure circularity at the product – excluding the production – level, the items perceived by the judges as strictly related to the production process rather than the product itself were eliminated, leading to an elimination of 12 items. Similarly, the four items related to the product's packaging were isolated by all the judges into an individual category related to packaging and not interpreted as part of the product, and they were therefore dropped. Finally, two items were not considered, by the judges, related to the circular economy and were, thus, also eliminated.

Concerning the items' clarity, some items were eliminated due to the way they were formulated. Firstly, two items were formulated in a negative sense and generated confusion among all the judges – some of the judges isolated them in a separate category – therefore, these two items were eliminated. Two items were considered as part of one single item and were thus merged, while three items were considered redundant and thus also eliminated. Lastly, the judges pointed out that one item was related to biological rather than technical cycles and was thus also dropped. Moreover, certain items were eliminated due to a very low clarity scale. In particular, items with an average clarity scale between 4 and 5 were considered clear; items with an average clarity scale between 2 and 3 were considered not clear enough and were, thus, reformulated based on the judges' comments; while the two items with an average clarity scale below 2 were considered too ambiguous and were, therefore, dropped.

Lastly, certain items which did not classify for removal, but were still not clear enough, were rephrased and modified. Specifically, twenty items were rephrased either because not clear enough or in order to improve their formulation, as suggested by the comments of the judges. After this round, 28 items were dropped from the initial pool of items – reducing the number of items from 106 to 78 – and 22 were rephrased or modified. The remaining items were divided into five categories, as follows:

Product Design:	25
Business Model:	14
Innovation:	5
Materials Management:	17
Customer Interaction:	17

Analysis of the Results

The aim of this round was both to ensure the validity of the constructs and identify those items which might have seemed ambiguous. Indeed, if, on the one side, among the pre-defined constructs, Product Design and Customer Interaction showed a good level of construct validity, on the other, Materials Management showed a very low construct validity level. Moreover, many items were found to be related to categories different than the pre-defined constructs, i.e., manufacturing and packaging, and were thus eliminated – consequently, the number of items dropped from 106 to 78. Many items intended as Materials Management and Business Model were not recognised and assigned to different categories. In order to assess this issue, many items were rephrased, and their meaning clarified.

The Item Placement Ratio for the Business Model and Materials Management categories is very low, indicating a low degree of agreement among the judges and a low degree of construct validity. Additionally, many items intended as Materials Management were assigned by the judges to Product Design, emphasising the possible existing relation between the two constructs. In sum, the results of this round suggest that the construct validity of the construct categories – and, particularly, of Business Model and Materials Management - must be improved.

6.1.2 Second Sorting Round

The judges selected for the second sorting round were invited to four individual meetings which lasted, on average, 41 minutes. During these meetings, the four judges were presented with a pool of items consisting of 78 statements, and they were asked to sort the items into five given construct categories. Specifically, the judges were asked to sort the items into the following constructs: Product Design, Business Model, Materials Management, Innovation, Customer Interaction. An 'I do not know' category was also provided to fit all those items that the judges found either too ambiguous (fitting in more than one category) or indeterminate (fitting in no category).

Inter-Rater Reliabilities

The inter-judge raw agreement scores averaged 55.34% while the Cohen's kappa scores averaged 0.4413 and the initial overall Item Placement Ratio was 66.67%. It can be noticed that the results improved if compared to the first round. This might be partly due to the fact that, in this round, the judges were asked to sort the items into given constructs categories – as opposed to identifying their own; and partly to the fact that we skimmed the number of items and improved their clarity. Albeit these improvements, the agreement scores, shown in *Tables 12* and *13*, are still relatively low. In particular, the Cohen's Kappa average score of 0.4431 is still below the acceptable level of 0.65.

	A	B	C	D
A		48.72%	53.85%	57.69%
B			61.54%	55.13%
C				55.13%
D				
Average				55.34%

Table 12 Raw Agreement Scores Second Sorting Round

	A	B	C	D
A		0.3652	0.4122	0.4611
B			0.5185	0.4473
C				0.4434
D				
Average				0.4413

Table 13 Cohen's Kappa Scores Second Sorting Round

The overall Item Placement Ratio suggests that 66.67% of the items were placed within the target constructs. A deeper look at the placement matrix shown in *Table 14*, and specifically at the off diagonals, makes us notice that the hit ratio for each construct is above 60% and that Innovation registered the highest placement ratio (85%). Moreover, as in the first sorting round, Business Model and Materials Management registered a low hit ratio compared to the other constructs (60.71% and 60.29%, respectively). In this round, however, Product Design's hit ratio is also relatively low (65%), probably due to the possible overlap between Product Design and Materials Management anticipated in the first sorting round. Although the hit ratio for the Innovation category is relatively high (85%), this construct highlighted one main issue in this round: all the four judges pointed out that the Innovation construct category was not well defined. This generated a systematic misplacement of many items designated to Product Design, which were assigned to the Innovation category instead.

Besides the presence of a significant cluster around the Product Design target category and the Materials Management actual category, an analysis of the off diagonals of the item placement matrix also shows some scattering. Particularly, ten items intended to be representative of Customer Interaction were assigned to Business Model, and eight Business Model items were assigned to Product Design. As a matter of fact, it emerges that some Business Model items were not easily understood and identified.

	Actual Categories							
Target Categories	Product Design	Business Model	Innovation	Materials Management	Customer Interaction	N/A	Tot	TGT
Product Design	65	3	9	18	2	3	100	65.00%
Business Model	8	34		6	7	1	56	60.71%
Innovation			17	3			20	85.00%
Materials Management	15	8	3	41		1	68	60.29%
Customer Interaction		10		1	51	6	68	75.00%
Total Item Placements	*312*							
Hits	*208*							
Overall Hit Ratio	*66.67%*							

Table 14 Item Placement Ratio Second Sorting Round

These results indicate that, so far in the development process, there is room for improvement in terms of construct validity, in order to ultimately obtain good reliability coefficients.

Changes Performed after the Second Round

After the second sorting round, several changes were made to both the items and the constructs. The changes made to the items were determined by the comments that the judges gave to our construct labels, the clarity and representativeness scales given by the judges to each item, and the judges' comments about the clarity and representativeness of the items.

More specifically, four items were dropped because the judges assigned them a very low clarity scale. Three items were dropped because the judges assigned them a very low representativeness scale, suggesting that the items might not to be representative of the category they associated them with. Lastly, one item was eliminated because considered redundant.

Nine items were modified in their formulation, as four of them registered a low level of representativeness, while five of them registered a low level of clarity. In sum, 8 items were dropped, and 9 items were modified; therefore, the number of items was reduced from 78 to 70 items, divided into the five constructs as follows:

Product Design:	24
Business Model:	13
Innovation:	5
Materials Management:	17
Customer Interaction:	11

Concerning the constructs' labels and definitions, as previously mentioned, Innovation represented a significant issue. In particular, all the four judges pointed out that the label

Innovation was too broad for our context, and this made unclear what the label represented. Therefore, the label Innovation was reviewed. As the definition of this construct refers to any new technology installed in the product which could enable circularity, the new and more specific label Technological Revolution was assigned to this category.

The judges also mentioned that Product Design and Materials Management are overlapping categories, and that Materials Management can be considered a subcategory, or a direct consequence, of Product Design. However, the two constructs remained separated, and the question on whether to merge them into a single category or not was postponed to the Instrument Testing stage of the process.

Lastly, the judges suggested that some of the items belonging to the Customer Interaction construct were more related to marketing and promotion, rather than to the interaction with customers. Therefore, Customer Interaction was relabelled to Promotion and Customer Involvement, in order to make sure that the construct category captures both aspects related to customers.

Analysis of the Results

In this second round, the results showed a general improvement, probably due to the fact that the judges were provided with the construct categories. However, Business Model and Materials Management were still the construct categories which registered the lowest degrees of agreement among the judges. On one hand, this was a consequence of the fact that Product Design and Materials Management may overlap. On the other hand, some Business Model items were not properly interpreted.

Innovation was the construct which represented the main issue in this round. Its definition was considered too broad for the context; therefore, the label Innovation was reviewed according to the specific definition meant for this construct – namely, any new technology installed in the product which could enable circularity – and a more appropriate label, Technological Revolution, was assigned to this category. The Customer Interaction construct category was also relabelled into Promotion and Customer Involvement, in order to capture both aspects related to customers.

The changes made according to the results of this round led to a drop in the number of items from 78 to 70. In sum, so far in the development process, there is room for improvement in construct validity, particularly for the Materials Management and Business Model construct categories. Moreover, an improvement of the results of the following rounds with respect to the two new reviewed construct categories (i.e., Technological Revolution and Promotion and Customer Involvement) is expected.

6.1.3 Third Sorting Round

The third sorting procedure reproduces the first one but uses the item pool refined after the first two sorting rounds. In this round, the pool counts 70 items, aiming to measure five constructs, i.e., Product Design, Business Model, Technological Revolution, Materials Management, and Promotion and Customer Involvement. The judges selected for the third sorting round were invited to four individual meetings which lasted, on average, 50 minutes. As for the first sorting round, the four judges were asked to sort the items into construct categories they had to identify themselves. The four judges identified, respectively, five, eleven, seven, and ten different categories. It can immediately be noticed how the number of different categories that the judges identified in this round was lower than in the first round. However, it is crucial to evaluate how many of the identified categories actually match our constructs definitions, which is an important indicator of construct validity. In order to do so, the same procedure as in the first round was applied, i.e., the categories identified by the judges were compared, and potentially matched, with the given constructs according to the judges' definitions of their construct categories. *Table 15* shows the judges' labels for the construct categories they identified, matched with our five pre-defined constructs.

		Judges			
		A	B	C	D
Constructs	Product Design	Design perspective	Longevity	Design improvement Durability	Modularity Lenght of life
	Business Model	Business model	Business model		Service
	Technological Revolution		IoT		Embedded technology
	Materials Management	Production and materials perspective	Use of natural resources in production Resource materials Recycling	Recycling	Resources
	Promotion and Customer Involvement	Costumer/end user perspective	Customer involvement Marketing		Communication Incentivise change
	NA	Lifecycle perspective - maintain, reuse, end of life	Intention Assumption Non-reliable third-party dependence	Remanufacturing Reuse Sustainable Manufacturing Visibility	After end of life Manufacturing During use

Table 15 Judges' Labels Third Sorting Round

The table shows that among the five categories identified by the first judge, four can be attributed to the pre-defined constructs, while one is labelled NA. Eight categories out of the eleven identified by the second judge are in line with our construct's definitions, while three are considered NA. Only three categories identified by the third judge fit our constructs definitions, while four are considered NA. Lastly, seven categories among the ten identified by the fourth judge are representative of our constructs while the remaining three are considered NA.

Overall, every judge identified at least one category that matches Product Design and at least one category that matches Materials Management. Conversely, one judge did not identify any category for Technological Revolution, while another judge did not identify Business Model, Technological Revolution and Promotion and Customer Involvement. These results suggest that the number of categories identified by the judges decreased compared to the first round, i.e., from an average of 12.5 categories in the first round to 8.25 in the second. However, Business Model was still not identified by one judge; Technological Revolution was, in this round, not identified by two judges (compared to only one in the first round); moreover, Promotion and Customer Involvement was not identified by one judge, while all four judges did in the first round. This discrepancy might find part of its explanation in the fact that one of the four judges interpreted the items using a different conceptualization of the circular economy than the one we adopted. More specifically, rather than its enablers, this judge focused on the four circularity loops described in the *Conceptual Framework*, and therefore assigned all of the items to these constructs' categories, thus not identifying three of our five original constructs. On the other hand, it can be noticed that the number of NA categories decreased compared to the first round, meaning that the pool of items was properly narrowed down to be more consistent with the target constructs.

Inter-Rater Reliabilities

The inter-judge raw agreement scores averaged 35.72% while the Cohen's Kappa scores averaged 0.1148 and the initial overall Item Placement Ratio was 39.64%. The level of agreement among the judges is lower than in the first two sorting rounds (47.96% in the first sorting round and 55.34% in the second). The average Cohen's Kappa score of 0.1148 is far below the acceptability threshold of 0.65. The Cohen's Kappa scores of the six pairs of judges decreased compared to the previous sorting rounds (0.2851 in the first round and 0.4413 in the second one). Nevertheless, this is mostly explained by the fact that, as previously mentioned, one of the four judges adopted a different conceptualization of the circular economy, thus not identifying three of our five construct categories. As a matter of fact, taking a closer look at the scores for each pair of judges, it can be noticed that the lowest scores are, indeed, registered for all pairs involving this particular judge (Judge C in *Tables 16* and *17*). *Tables 16* and *17* show the agreement scores for each pair of judges.

	A	B	C	D
A		32.86%	30.00%	40.00%
B			31.43%	48.57%
C				31.43%
D				
Average				35.72%

Table 16 Raw Agreement Scores Third Sorting Round

	A	B	C	D
A		0.0976	-0.0639	0.2020
B			0.0210	0.3487
C				0.0835
D				
Average				0.1148

Table 17 Cohen's Kappa Scores Third Sorting Round

From the analysis of the item-placement matrix shown in *Table 18*, it can be noticed that the 39.64% of the items were placed within the target constructs. The overall hit ratio decreased compared to the second sorting round but improved compared to the first one. This result is promising, if we consider that, during the first and third sorting rounds, the judges had to identify their own categories, and many of them were considered as NA categories – leading to a high number of items placed in the NA category, and therefore to low hit ratios. During the second round, instead, the judges were provided with constructs and, thus, a lesser number of items were placed in the NA category. As a result, the fact that the hit ratio of the third round was higher than the one registered in the first round is a positive sign, even though it is lower than the one registered in the second round.

The highest hit ratios were registered by Technological Revolution and Materials Management (both at 50%), followed by Promotion and Customer Involvement (40.91%), Product Design (37.50%) and Business Model (25%). These results decreased compared to the second round; moreover, results for Product Design, Technological Revolution and Promotion and Customer Involvement also decreased compared to the first round. This might, again, be explained by the fact that one judge followed a different conceptualization of the circular economy, and did not identify the construct categories Business Model, Technological Revolution and Promotion and Customer Involvement, leading to a high number of items in the NA category.

The off diagonal of the matrix suggests the presence of some clusters outside the targets. For instance, many items intended as either Product Design or Business Model, have been sorted in the Materials Management category.

	Actual Categories							
Target Categories	Product Design	Business Model	Technological Revolution	Materials Management	Promotion and Customer Involvement	N/A	Tot	TGT
Product Design	36			11	2	47	96	37.50%
Business Model	4	13		10	3	22	52	25.00%
Technological Revolution	5		10			5	20	50.00%
Materials Management	5			34	1	28	68	50.00%
Promotion and Customer Involvement				8	18	18	44	40.91%
Total Item Placements	*280*							
Hits	*111*							
Overall Hit Ratio	39.64%							

Table 18 Item Placement Ratio Third Sorting Round

Changes Performed after the Third Round

After the third sorting round, the aim was to narrow the pool of items to a level that could ensure parsimony and construct validity in light of the final sorting round preceding the Instrument Testing. Therefore, our judgement in modifying and dropping items was stricter after the third round compared to the previous ones. Although the judges found the items to be generally clear, 32 items were dropped and 12 were modified - resulting in a list of 38 statements.

Changes were made to those items which proved to be either still unclear or placed systematically outside the target constructs. More specifically, some of the items were reformulated because judges suggested that the way they were presented was more similar to an intention rather than an actual state of the product. Other items were modified because judges consistently placed them outside the target constructs, and given their relevance in terms of content validity, it was more ideal to reformulate them in a more straightforward manner rather than drop them from the list.

The dropped items, instead, were those sorted out consistently outside the target constructs and/or inside NA categories (which were, in this round, mainly related to either manufacturing or product lifecycle). Secondly, items considered not relevant to product circularity by at least two judges were also dropped. Lastly, a few items were eliminated because considered redundant. The remaining 38 items are divided into five categories, as follows:

Product Design:	10
Business Model:	10
Technological Revolution:	5
Materials Management:	8
Promotion and Customer Involvement:	5

Analysis of the Results

In this round, it was essential to evaluate whether the changes made in the previous rounds were able to improve construct validity. It might be noticed that, generally, the categories identified by the judges in this round were in line with the pre-defined constructs, suggesting higher construct validity compared to the previous rounds. Additionally, only a few of the categories were considered NA. Another encouraging aspect regards the Materials Management pre-defined construct, which was not properly recognised in the first round. Conversely, in this sorting round, all the judges created at least a Materials Management related category, proving an increase in the validity of the construct. On the other hand, both Technological Revolution and Business Model construct validity still have room for improvement.

It could be noticed that one judge adopted a completely different conceptualization of the circular economy when sorting out the items; rather than its enablers, this judge assigned items to categories representing the four circularity loops described in the *Conceptual Framework* and, therefore, from his side, the Business Model, Technological Revolution and Promotion and Customer Involvement constructs were not identified. As a consequence, the level of agreement among judges decreased compared the previous rounds.

Lastly, it is worth mentioning that the level of clarity of items was on average very high, suggesting that the items were properly formulated, and their meaning was easily understandable.

6.1.4 Fourth Sorting Round

The aim of this final round was to further refine the pool of items, in order to ensure a certain level of parsimony, in preparation for the Instrument Testing stage. According to the Q-Sort method implemented by Moore and Benbasat (1991), the fourth and final round followed the same procedure as the second one. Again, the four selected judges were invited to individual meetings which lasted, on average, 36 minutes. During these meetings, the four judges were presented with a pool of items consisting of 38 statements, and they were asked to sort the items into five given construct categories. Specifically, judges were asked to sort the items into the following constructs: Product Design, Business Model, Materials Management, Technological Revolution, Promotion and Customer Involvement. An 'I do not know' category was, again, provided to fit all those items judges considered either too ambiguous (fitting in more than one category) or indeterminate (fitting in no category).

Inter-Rater Reliabilities

In this final sorting round, the inter-judge raw agreement scores averaged 74.56% while the Cohen's Kappa scores averaged 0.6774 and the overall placement ratio of items within the target constructs was 80.92%. The level of agreement among judges reached a relatively high level (74.56% on average) with the agreement among the pairs of judges above 71%. These scores significantly improved compared to the previous sorting rounds. Specifically, compared to the second round, characterized by the same procedure as the final round, the level of agreement improved of almost 20%. Similarly, Cohen's Kappa scores improved. Only one pair of judges registered a score below the threshold (0.6337), and the overall average of Cohen's Kappa scores was 0.6777, thus above the acceptability threshold of 0.65. Results for the levels of agreement are shown in *Tables 19* and *20*.

	A	B	C	D
A		71.05%	76.32%	76.32%
B			78.95%	71.05%
C				73.68%
D				
Average				74.56%

Table 19 Raw Agreement Scores Fourth Sorting Round

	A	B	C	D
A		0.6378	0.7005	0.6913
B			0.7375	0.6337
C				0.6634
D				
Average				0.6774

Table 20 Cohen's Kappa Scores Fourth Sorting Round

Looking at the Item Placement Ratio, the 80.92% of items was placed within the target constructs, resulting in a significantly higher overall hit ratio than the previous rounds (38.44% in the first round, 66.67% in the second and 39.64% in the third). The item placement matrix, shown in *Table 21*, and the individual hit ratios for each target construct confirm such improvement. For instance, Materials Management reached a 100% hit ratio, meaning that all items explaining this construct category were correctly placed by the judges. Moreover, 85%

of items measuring Technological Revolution or Promotion and Customer Involvement were also assigned to the target constructs. Business Model registered a 72.5% hit ratio, while the lowest individual hit ratio was Product Design with 70% of items placed within the target constructs.

The off diagonals of the matrix confirm these results, as only two off-target clusters could be identified. Some Product Design items were placed within the Materials Management construct category. However, this is not surprising since it also emerged in the previous rounds that Product Design and Materials Management overlap, and that Materials Management could, indeed, be considered as a subcategory of Product Design. The second cluster concerns Business Model, since some Business Model items were placed in Promotion and Customer Involvement or Materials Management. However, as the number of misplaced items is very low in both cases, these off diagonals do not significantly undermine construct validity. Overall, all the analysed inter-judge agreement scores show significant improvements, indicating a high level of construct validity and high potential for good reliability coefficients.

	Actual Categories							
Target Categories	Product Design	Business Model	Technological Revolution	Materials Management	Promotion and Customer Involvement	N/A	Tot	TGT
Product Design	28		2	8	2		40	70.00%
Business Model	1	29		4	5	1	40	72.50%
Technological Revolution	2		17	1			20	85.00%
Materials Management				32			32	100.00%
Promotion and Customer Involvement		2		1	17		20	85.00%
Total Item Placements	*152*							
Hits	*123*							
Overall Hit Ratio	80.92%							

Table 21 Item Placement Ratio Fourth Sorting Round

Changes Performed after the Fourth Round

The aim of the changes performed after the final sorting round was to significantly reduce the number of items and ensure parsimony in light of the Instrument Testing stage – but keeping at least five items per construct category. Moreover, some items were further reformulated and merged after the comments and suggestions offered by the judges. As a result, five items were modified, six were dropped and eight items were merged into three.

Although all the items, with only very few exceptions, were considered clear, judges provided suggestions and comments on how to further improve them. For the majority of cases, these suggestions concerned reducing the number of words in the statements and making them as easy as possible to understand. As a result, five of the 38 items were modified and reformulated.

Only one item was dropped, as it was consistently placed off-target, while the other five were merged with other items. While reading the items, some judges thought that some of them were redundant. We indeed noticed that some of them were stated in a similar way even though they have a different meaning. For instance, within the Business Model construct, three different items referring to the concept of providing a service rather than ownership of a product, namely pay-per-use, renting and leasing business models separately. For the sake of clarity and parsimony, the three items were merged into one. In the same way, within the Materials Management construct two items referring to upcycling and recycling were merged. Lastly, we merged two items inside the Product Design construct, regarding the reuse of materials and components. The new merged item includes both their reuse in the production of same and of other product categories.

Overall, after merging and dropping items, the final pool of items counts 32 statements (see Appendix E) intended to explain five constructs, as follows:

Product Design:	9 items
Business Model:	7 items
Technological Revolution:	5 items
Materials Management:	6 items
Promotion and Customer Involvement:	5 items

Analysis of the Results

In this last round, the level of agreement among judges and pair of judges reached a relatively high level, showing a significant improvement compared to the previous sorting rounds. Indeed, the results suggest a high level of construct validity and therefore high potential for good reliability coefficients. Despite these promising results, for the sake of parsimony, the list of items was further skimmed, reaching a total of 32 items. It is believed that, having five pre-defined constructs, 32 is a reasonable number of items. All the pre-defined construct categories are, indeed, represented by at least five items.

6.2 Discussion

6.2.1 Construct Categories

As described in the *Research Design and Methodology*, the aim of the first two stages of the instrument development process, after identifying and defining the variables of the circular economy, was to assess content and construct validity. The analysis of the results shows that an overall good level of validity was reached – indicating that the instrument covers all the items to reflect the definition of the circular economy. Nevertheless, the four sorting rounds highlighted some general recurring patterns, related to the five construct categories representing the determinants of the latent variable in analysis.

A first recurrent issue presented by the judges during the Scale Development stage is related to the possible overlap existing between Product Design and Materials Management, which led the judges to think that the two constructs may be representing the same variable and could, therefore, be merged. This opinion stems from the fact that, in practice, product design represents an early stage of a product's development, and most of the decisions concerning the materials and resources deployed when manufacturing a product are, indeed, made during the product design stage. In this light, it could be inferred that all the items included in the Materials Management construct are, actually, a consequence of product design decisions and could, therefore, be part of the Product Design construct. Albeit valuing and agreeing with the judges' opinion, we decided not to merge the two constructs at this stage of the process, and to postpone this decision to the evaluation of the factor analysis results performed during the Instrument Testing stage. This choice was based on the fact that the items included in the Product Design and Materials Management constructs were selected from two slightly but still different lines of research on the circular economy: on the one hand, from the literature concerning circular product design, items describing the strategic decisions regarding the physical durability, reuse and maintenance, as well as remanufacturing of the product were formulated; on the other hand, the items selected from the literature on sustainable materials management are more specifically related to what materials and resources to use in manufacturing the product, their amount, as well as their handling at the end of the products' lifecycle.

Another recurring pattern, which characterized all sorting rounds, is related to the Business Model construct. Specifically, the items belonging to this construct generated some confusion among the judges in each round, leading them to misplace these items both when they had to identify their own categories, but also when they were provided with the pre-defined constructs. This issue could be attributed to the fact that many different definitions of the concept of business model exist, which may include several aspects characterizing a product. As a matter of fact, as the judges commented, some definitions of business model include marketing and promotion decisions, and/or product design strategies. As a result, if a broad definition is adopted when interpreting the items, such constructs may be considered as subcategories of Business Model. It can be inferred that providing the judges with a more precise definition of the Business Model construct, specifying the scope that our construct intends to cover, could have helped the judges to fully understand the respective items. It can, in fact, be noticed that the misplacement of Business Model items was reduced from the second to the fourth round, when the overall number of items had considerably decreased, and the statements had been modified in order to be clearer in their meaning.

During the first sorting round, it emerged that many of the items initially included in the pool – mainly among those related to Product Design and Materials Management – were more associated with the product's manufacturing process, which was identified as a separate category by all of the four judges. Similarly, in the third round, the product's lifecycle emerged as a category that we did not identify as a separate pre-defined construct. These two rounds – both characterized by the fact that the judges were not provided with the categories and had to identify their own – highlighted that there are aspects influencing product circularity not covered by the instrument scale developed in this study. This could indicate that the latent variable the instrument is measuring is missing some of the factors defining it. However, as the circular economy perspective adopted in this research was that of a second-order formative construct, only those factors defined as its determinants (i.e., directly influencing the level of product circularity) were considered. For this reason, only those product's characteristics defined by the literature as catalysts or enablers of the circular economy and therefore determinants of it, were included in the research. The product's manufacturing process can, indeed, be considered as an additional determinant of the degree product circularity, but beyond the scope of this study and to be assessed separately. For this reason, most – if not all – of the items referred, in the judges' opinion, to the product's manufacturing process were eliminated from the pool of items. On the other hand, we realized that the product's lifecycle can be considered, instead, more as an alternative perspective of product's circularity than the one adopted in this research, rather than an additional determinant of the circular economy. For this reason, most of these items remained in the pool, but they were reformulated or modified in order to improve their clarity, thus the instrument's validity.

The construct category referred to new technologies, that if embedded in the products may enable circularity, was initially misunderstood by many of the judges and caused confusion and misplacement during the first two rounds. As explained in the *Analysis of Results* section, during the second round – when labels for the constructs were provided – this issue was pointed out by all of the judges. As a result, the initial label Innovation was modified in order to make it more clearly related to the construct's definition. The updated label, Technological Revolution, was properly interpreted by the judges in the fourth round – indicating that the construct was, indeed, properly represented by its items and that the initial confusion was due to the construct's label and not to the construct itself. The idea of renaming the label referring directly to the technological revolution emerges from the fact that the judges in the first round identified *IoT* and *embedded technology* as construct categories – and this was confirmed in the third round, in which construct categories labelled after new technologies were, again, created. Given that our aim was to render the construct's label more representative of the construct's definition, which does revolve around the deployment of IoT and sensor technology, we decided to rename the category in a more straightforward way.

Lastly, the construct category related to customer involvement and promotion activities for the circular economy was, by some of the judges, considered as a more isolated category, not playing a direct role in enhancing product circularity. Even though this idea may suggest that this factor influences the circular economy differently from product design or business models, and probably plays a role at a different level than the product one, we decided to keep the construct category unmodified during the whole Scale Development stage (also because the items belonging to this category were generally properly placed), and the decision on whether to keep it as a circular economy factor or not was postponed, as in the first case, to the Instrument Testing stage.

6.2.2 Items

The changes made to the pool of items throughout the four rounds, in terms of elimination and modification of the statements, were performed with the aim of improving validity. At the end of the Scale Development process, a total of 74 items were eliminated and 48 statements were modified, suggesting that the initial pool of items was not clear and representative to an acceptable level of the variable under study.

In addition to content and construct validity, considerations on the instrument's parsimony were made, with the aim of creating an instrument constituted of a relatively low number of items, in turn formulated as statements consisting of a low number of words. To this end, many items were eliminated, and many were modified in order to make them shorter.

Throughout the four rounds, the inter-rater reliabilities experienced a gradual increase indicating that the level of validity of the instrument improved during the process. At the end of the fourth round, the final list of items consists of 32 relatively short statements and the resulting instrument scale is characterized by an acceptable Cohen's Kappa score and a high Item Placement Ratio, paving the way for high reliability coefficients. *Table 22* provides a list of an exemplifying item per each construct, and Appendix E provides the complete final list of items. To conclude, being the Q-Sort method implemented in the Scale Development stage an iterative procedure, additional sorting rounds could be performed before proceeding to the Instrument Testing stage, in order to further refine the items and increase validity scores. However, we are confident that the instrument is, as developed thus far, appropriate for being directly tested.

Construct	*Item*
Product Design	Our product is designed for physical durability
Business Model	Our product is delivered on a pay-per-use basis, given on lease or rented out
Technological Revolution	IoT technology is embedded in our product to provide knowledge on its condition, allowing for the implementation of predictive maintenance schemes
Materials Management	Our product's materials can be reprocessed into materials with equivalent or improved properties
Promotion and Customer Involvement	Our product is sold with information regarding what customers should do after usage

Table 22 Exemplifying Item per Construct Category

7. Conclusion and Further Research

The circular economy has recently emerged as a possible alternative to the linear economic model *take-make-dispose*. Indeed, the circular economy might be a solution to be adopted by companies in light of the increasing environmental degradation and climate change. In this setting, it emerges the need for the development of instruments able to evaluate whether companies are making movements towards this direction. Specifically, the reason for conducting the present research stems from the fact that the circular economy literature lacks an instrument able to measure the degree of circularity in products, considered at the basis of circular economy implementation.

In the literature there can be found three levels of implementation of the circular economy: the macro, meso and micro levels; however, the indicators able to measure circular economy at the nano – or product – level are characterised by several limitations, as for instance, they do not consider multiple crucial aspects which are essential in evaluating the progress towards more circular models.

Therefore, this study aims at developing an instrument able to measure the degree of circularity for technical – as opposed to biological – products, for the company in its supply chain based on the parameters which have been defined in the literature as catalyst of product circularity, i.e., product design, business model, technological revolution, materials management and customer involvement. The development of such an instrument would provide the academia with a tool which, combined with other sustainability measures, would enrich the literature and the understanding of products circularity.

In order to do so, this research adopts an exploratory sequential mixed methods approach and follows a three-stage process aimed at ensuring the validity, reliability and parsimony of the instrument. Specifically, this research reports the first two stages of this process, i.e., Item Creation – which entails the creation of a pool of items to match each construct definition and ensure content validity; and Scale Development – which includes four Q-sorting rounds involving sixteen judges and aims at sorting items into construct categories and examining inter-rater reliabilities, in order to ensure construct validity. The third and last stage, i.e., Instrument Testing – which consists in administering the survey instrument to a pilot sample to check the reliability of the construct categories – is beyond the scope of our research.

The final result of the study and therefore of the two stages of the process is a scale instrument consisting of 32 items, representing five constructs categories: product design, business model, technological revolution, materials management and promotion and customer involvement. Particularly, the aim of the first two stages of the instrument development process, after having identified and defined the variables of the circular economy, was to assess content and construct validity. The analysis of the results shows that an overall good level of validity was reached – indicating that the instrument covers all the items to reflect the definition of the circular economy. Nonetheless, it is necessary to mention some patterns which have emerged during the process. They concern both the five construct categories and the list of items. Firstly, it has been highlighted how the two construct categories of Product Design and Materials Management may overlap. This opinion stems from the fact that, in practice, many materials and resource deployment decisions concerning a product are made during the design phase and therefore many Materials Management items seem to be actually related to Product Design. However, since the Materials Management construct category concerns specifically sustainable materials management while Product Design items concern physical durability, reuse and maintenance of the product, in this research, the two construct categories have been kept separately.

Besides the construct categories identified in this study referred to those product's characteristics defined by the literature as catalysts or enablers of the circular economy, i.e., product design, business model, technological revolution, materials management and customer involvement, it has emerged how other aspects of the circular economy could be taken into account since they might influence product circularity, such as products' manufacturing process and products' lifecycle. However, these additional determinants of the degree of product circularity are beyond the scope of this study and to be assessed separately.

During the process, two construct categories have been reformulated. On the one side, the Technological Revolution category was firstly defined as Innovation. However, this term was considered too broad and often misinterpreted. Thus, given that our aim was to render the construct's label more representative of the construct's definition, which does revolve around the deployment of IoT and sensor technology, this construct category has been renamed in a more straightforward way, i.e., Technological Revolution. On the same line, the construct category related to customer involvement and promotion activities for the circular economy changed label from Customer Interaction to Promotion and Customer Involvement.

As far as the list of items is concerned, the first stage of the process leads to the creation of 106 items, which have been further skimmed during the second stage. The final list of items includes 32 items, nine representing the Product Design construct category, seven Business Model, five Technological Revolution, six Materials Management and five Promotion and Customer Involvement; all of them reached high levels of clarity and representativeness of the constructs.

Specifically, the Product Design construct includes items related to design for durability, maintenance and reparation, reuse and remanufacture, dis- and re- assembly, modular design and biomimicry, design for pleasurable experiences and meaningful design.

Business Model items refer to the implementation by companies of several business models which aim at either slowing or closing the loops, as for instance, the *Access and Performance Model*, the *Extending Product Value Model*, the *Classic Long-Life Model*, and the *Encourage Sufficiency Model*.

Materials Management items refer to minimising the use of both materials, resources and new raw materials in products as well as minimizing the amount of materials designated to landfill and incineration. Additionally, they include the reuse of parts and components and of recycled materials as feedstock, and lastly the recycling of products and materials after usage.

Technological Revolution includes items related to embedded IoT technology to collect data on the product's condition, facilitating decision making on the next use cycle for returned products, i.e., reuse, remanufacture, recycle; to provide knowledge both products' condition, allowing for the implementation of predictive maintenance schemes, and on products' composition and condition, enabling product design improvements. It includes items related to tracking technology on the one side, in order to provide knowledge on products' location and condition, improving supply chain and logistics operations' transparency and visibility and, on the other side, sensors to provide insights into the composition of multiple types of materials, improving the precision of sorting activities.

Lastly, the Promotion and Consumer Involvement construct includes items related to customers' involvement in circularity activities, the promotion of circularity through both advertising activities, and communication materials (e.g. company's website), reuse and recycle promotion and after-usage information.

The limitations of this study regard mainly the scope of the research and the methodology; such limitations could be considered the starting point for future research and to refine and improve further the instrument. Specifically, the instrument developed is meant to be applied exclusively to technical cycles – as it is not related to biological products and strategies and thus it cannot be representative of biological cycles; therefore, further research on the biological cycles are beneficial. Moreover, the present instrument might be improved if adapted to the specific characteristics of different industries. Furthermore, as stated above, the present instrument does not consider a detailed analysis of products' manufacturing processes and lifecycle. Therefore, the present instrument could be improved including these aspects as well as an assessment of the circular economy at the micro and meso level, in order to develop a comprehensive understanding of the circular supply chain and its determinants.

The limitations concerning the methodology refer mostly to the Scale Development stage and the Instrument Testing stage of the process. For instance, the results of the Scale Development depend on the judges involved and their background and knowledge, thus the involvement of different judges might have changed the results of these stages. Moreover, being the Q-Sort method implemented in the Scale Development stage an iterative procedure, additional sorting rounds could be performed before proceeding to the Instrument Testing stage, in order to further refine the items and increase validity scores. Lastly, as the final Instrument Testing stage of the process was beyond the scope of this research, the instrument scale consisting of 32 items hereto developed cannot be considered complete, and a pilot test – accompanied, eventually, by a final field test – should be performed to finalize the instrument.

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Appendix

Appendix A – STATA Output for Agreement Scores First Sorting Round

1 . *(4 variables, 106 observations pasted into data editor)

2 . tabulate a b

A	B 0	1	2	3	4	5	Total
0	19	4	0	0	6	2	31
1	23	2	0	0	10	2	37
2	4	2	4	0	1	1	12
3	0	0	0	6	0	0	6
5	4	2	0	0	1	13	20
Total	50	10	4	6	18	18	106

3 . kap a b

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
41.51%	21.04%	0.2592	0.0430	6.03	0.0000

4 . tabulate a c

A	C 0	1	2	4	5	Total
0	17	10	0	3	1	31
1	18	5	0	12	2	37
2	4	0	4	1	3	12
3	5	1	0	0	0	6
5	7	0	0	0	13	20
Total	51	16	4	16	19	106

5 . kap a c

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
36.79%	23.15%	0.1775	0.0467	3.80	0.0001

6 . tabulate a d

A	D 0	1	3	5	Total
0	23	6	0	2	31
1	24	13	0	0	37
2	3	9	0	0	12
3	0	0	6	0	6
5	6	1	0	13	20
Total	56	29	6	15	106

7 . kap a d

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
51.89%	27.99%	0.3319	0.0544	6.10	0.0000

8 . tabulate b c

B	C 0	1	2	4	5	Total
0	28	11	0	8	3	50
1	3	2	0	0	5	10
2	0	0	4	0	0	4
3	5	1	0	0	0	6
4	8	2	0	8	0	18
5	7	0	0	0	11	18

Total	51	16	4	16	19	106

9 . kap b c

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
50.00%	29.87%	0.2871	0.0535	5.37	0.0000

10 . tabulate c d

	D				
C	0	1	3	5	Total
0	32	10	5	4	51
1	6	9	1	0	16
2	0	4	0	0	4
4	15	1	0	0	16
5	3	5	0	11	19
Total	56	29	6	15	106

11 . kap c d

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
49.06%	32.08%	0.2499	0.0538	4.64	0.0000

Appendix B – STATA Output for Agreement Scores Second Sorting Round

```
1 . drop _all

2 . *(4 variables, 78 observations pasted into data editor)

3 . tabulate a b
```

A	B 0	1	2	3	4	5	Total
1	1	11	7	0	14	0	33
2	1	1	4	0	2	1	9
3	0	0	0	5	1	0	6
4	2	1	2	0	6	0	11
5	2	2	3	0	0	12	19
Total	6	15	16	5	23	13	78

```
4 . kap a b
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
48.72%	19.21%	0.3652	0.0517	7.07	0.0000

```
5 . tabulate a c
```

A	C 0	1	2	3	4	5	Total
1	0	15	4	2	12	0	33
2	2	0	7	0	0	0	9
3	0	0	1	4	1	0	6
4	0	3	3	0	5	0	11
5	1	3	4	0	0	11	19
Total	3	21	19	6	18	11	78

```
6 . kap a c
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
53.85%	21.48%	0.4122	0.0551	7.49	0.0000

```
7 . tabulate a d
```

A	D 0	1	2	3	4	5	Total
1	0	16	2	7	7	1	33
2	1	0	6	0	0	2	9
3	0	0	0	3	3	0	6
4	0	1	2	2	6	0	11
5	1	2	1	0	1	14	19
Total	2	19	11	12	17	17	78

```
8 . kap a d
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
57.69%	21.50%	0.4611	0.0559	8.25	0.0000

```
9 . tabulate b c
```

B	C 0	1	2	3	4	5	Total
0	2	2	1	0	1	0	6
1	0	13	1	1	0	0	15
2	1	1	8	0	5	1	16
3	0	0	0	4	1	0	5

4	**0**	**5**	**6**	**1**	**11**	**0**	**23**
5	**0**	**0**	**3**	**0**	**0**	**10**	**13**
Total	**3**	**21**	**19**	**6**	**18**	**11**	**78**

10 . **kap b c**

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
61.54%	**20.12%**	**0.5185**	**0.0551**	**9.40**	**0.0000**

11 . **tabulate b d**

	D						
B	0	1	2	3	4	5	Total
0	**1**	**2**	**0**	**1**	**1**	**1**	**6**
1	**1**	**9**	**1**	**4**	**0**	**0**	**15**
2	**0**	**1**	**7**	**1**	**4**	**3**	**16**
3	**0**	**0**	**0**	**3**	**2**	**0**	**5**
4	**0**	**7**	**3**	**3**	**10**	**0**	**23**
5	**0**	**0**	**0**	**0**	**0**	**13**	**13**
Total	**2**	**19**	**11**	**12**	**17**	**17**	**78**

12 . **kap b d**

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
55.13%	**18.82%**	**0.4473**	**0.0529**	**8.45**	**0.0000**

13 . **tabulate c d**

	D						
C	0	1	2	3	4	5	Total
0	**1**	**0**	**1**	**0**	**0**	**1**	**3**
1	**0**	**12**	**1**	**6**	**2**	**0**	**21**
2	**1**	**1**	**8**	**0**	**5**	**4**	**19**
3	**0**	**1**	**0**	**3**	**2**	**0**	**6**
4	**0**	**5**	**1**	**3**	**8**	**1**	**18**
5	**0**	**0**	**0**	**0**	**0**	**11**	**11**
Total	**2**	**19**	**11**	**12**	**17**	**17**	**78**

14 . **kap c d**

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
55.13%	**19.38%**	**0.4434**	**0.0540**	**8.20**	**0.0000**

Appendix C – STATA Output for Agreement Scores Third Sorting Round

```
1 . drop a-d

2 . *(4 variables, 70 observations pasted into data editor)

3 . tabulate a b
```

A	B 0	1	2	3	4	5	Total
0	12	2	0	0	14	6	34
1	7	2	0	5	3	0	17
2	0	0	3	0	1	0	4
4	4	0	0	0	6	0	10
5	3	0	0	0	2	0	5
Total	26	4	3	5	26	6	70

```
4 . kap a b
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
32.86%	25.59%	0.0976	0.0588	1.66	0.0485

```
5 . tabulate a c
```

A	C 0	1	4	Total
0	14	9	11	34
1	12	4	1	17
2	4	0	0	4
4	5	2	3	10
5	1	1	3	5
Total	36	16	18	70

```
6 . kap a c
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
30.00%	34.20%	-0.0639	0.0745	-0.86	0.8043

```
7 . tabulate a d
```

A	D 0	1	2	3	4	5	Total
0	13	7	3	0	2	9	34
1	4	5	0	5	2	1	17
2	1	0	3	0	0	0	4
4	4	0	0	0	5	1	10
5	2	1	0	0	0	2	5
Total	24	13	6	5	9	13	70

```
8 . kap a d
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
40.00%	24.82%	0.2020	0.0602	3.36	0.0004

```
9 . tabulate b c
```

B	C 0	1	4	Total
0	10	10	6	26
1	0	4	0	4
2	3	0	0	3
3	5	0	0	5

4	16	2	8	26
5	2	0	4	6
Total	36	16	18	70

```
10 . kap b c
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
31.43%	29.96%	0.0210	0.0675	0.31	0.3779

```
11 . tabulate b d
```

B	D 0	1	2	3	4	5	Total
0	9	6	2	0	2	7	26
1	0	4	0	0	0	0	4
2	0	0	3	0	0	0	3
3	0	0	0	5	0	0	5
4	15	3	1	0	7	0	26
5	0	0	0	0	0	6	6
Total	24	13	6	5	9	13	70

```
12 . kap b d
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
48.57%	21.04%	0.3487	0.0549	6.35	0.0000

```
13 . tabulate c d
```

C	D 0	1	2	3	4	5	Total
0	13	3	3	5	6	6	36
1	4	8	2	0	2	0	16
4	7	2	1	0	1	7	18
Total	24	13	6	5	9	13	70

```
14 . kap c d
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
31.43%	25.18%	0.0835	0.0584	1.43	0.0766

Appendix D – STATA Output for Agreement Scores Fourth Sorting Round

```
1 . drop a-d

2 . *(4 variables, 38 observations pasted into data editor)

3 . tabulate a b
```

A	B 1	2	3	4	5	Total
0	0	1	0	0	0	1
1	5	1	1	0	1	8
2	0	4	0	0	2	6
3	0	0	4	0	1	5
4	2	1	0	9	1	13
5	0	0	0	0	5	5
Total	7	7	5	9	10	38

```
4 . kap a b
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
71.05%	20.08%	0.6378	0.0788	8.09	0.0000

```
5 . tabulate a c
```

A	C 1	2	3	4	5	Total
0	0	1	0	0	0	1
1	6	1	1	0	0	8
2	0	6	0	0	0	6
3	1	0	4	0	0	5
4	3	1	0	9	0	13
5	0	1	0	0	4	5
Total	10	10	5	9	4	38

```
6 . kap a c
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
76.32%	20.91%	0.7005	0.0806	8.69	0.0000

```
7 . tabulate a d
```

A	D 1	2	3	4	5	Total
0	0	1	0	0	0	1
1	5	1	0	2	0	8
2	0	5	0	0	1	6
3	1	0	4	0	0	5
4	0	0	0	12	1	13
5	0	1	0	1	3	5
Total	6	8	4	15	5	38

```
8 . kap a d
```

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
76.32%	23.27%	0.6913	0.0832	8.31	0.0000

```
9 . tabulate b c
```

B	C 1	2	3	4	5	Total
1	7	0	0	0	0	7

2	0	6	0	1	0	7
3	0	0	5	0	0	5
4	1	0	0	8	0	9
5	2	4	0	0	4	10
Total	10	10	5	9	4	38

10 . kap b c

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
78.95%	19.81%	0.7375	0.0790	9.33	0.0000

11 . tabulate b d

B	D 1	2	3	4	5	Total
1	4	0	0	3	0	7
2	0	6	0	1	0	7
3	1	0	3	1	0	5
4	0	0	0	9	0	9
5	1	2	1	1	5	10
Total	6	8	4	15	5	38

12 . kap b d

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
71.05%	20.98%	0.6337	0.0802	7.90	0.0000

13 . tabulate c d

C	D 1	2	3	4	5	Total
1	5	0	1	4	0	10
2	0	8	0	0	2	10
3	1	0	3	1	0	5
4	0	0	0	9	0	9
5	0	0	0	1	3	4
Total	6	8	4	15	5	38

14 . kap c d

Agreement	Expected Agreement	Kappa	Std. Err.	Z	Prob>Z
73.68%	21.81%	0.6634	0.0821	8.09	0.0000

Appendix E – Final List of Items

Constructs	*Items*
Product Design	Our product is designed for physical durability
	Our product is designed to be liked or trusted longer by customers, through timeless aesthetics and pleasurable experiences
	Our product is easy to maintain and repair
	Our product's individual components and materials can be reused in the production of the same or other product categories
	Our product's parts and components fit other products as well
	Our product's parts and components can be easily separated and reassembled
	Our product can be easily upgraded, i.e. its quality, value, effectiveness or performance can be improved to enhance its competitiveness and functionality
	Our product is produced in modular design, i.e. in functional clusters of components with similar technical durability and technology change rate
	Our product is designed based on biomimicry, i.e. creating sustainable innovation by applying strategies found in nature
Business Model	Our product is delivered on a pay-per-use basis, given on lease or rented out
	Our product is delivered through performance agreements, i.e. customers buy a predefined service and quality level, and we commit to guaranteeing a specific result
	At the end of its life-cycle, our product is collected through take-back, trade-in or buy-back schemes
	At the end of its life-cycle, our product is restored to a "as new" state to be resold to price-sensitive customers
	We deliver a high-quality product, accompanied by high levels of maintenance and repair services
	We follow a non-consumerist approach to reduce end-user consumption
	We address "green" interests by producing our product with discarded materials collected/sourced through take-back systems
Technological Revolution	IoT technology is embedded in our product to collect data on the product's condition, facilitating decision making on the next use cycle for returned products, i.e reuse, remanufacture, recycle
	IoT technology is embedded in our product to to provide knowledge on its condition, allowing for the implementation of predictive maintenance schemes
	IoT technology is embedded in our product to provide knowledge on its composition and condition, enabling product design improvements
	Tracking technology is embedded in our product to provide knowledge on its location and condition, improving supply chain and logistics operations' transparency and visibility
	Sensors are embedded in our products to provide insights into the composition of multiple types of materials, improving the precision of sorting activities

Materials Management	Our product is produced with the minimum possible amount of materials and resources
	Our product's amount of new raw materials is minimized
	Our product's materials destined to landfill or incineration are minimized
	Part of our product's feedstock comes from reused parts and components
	Part of our product's feedstock comes from recycled materials
	Our product's materials can be reprocessed into materials with equivalent or improved properties
Promotion and Customer Involvement	We involve customers in our circularity activities
	We promote circularity through advertising activities
	We promote circularity on our communication materials (e.g. company's website)
	We promote our product's reuse and recycle
	Our product is sold with information regarding what customers should do after usage