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“THE ROLE OF INDUSTRY 4.0 TECHNOLOGIES IN IMPLEMENTING CIRCULAR ECONOMY STRATEGIES”

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A mia madre e mio padre

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Firma dello studente

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INTRODUCTION

Circular Economy is gaining increasing attention worldwide as a way to overcome the linear "take, make, dispose" economic model, that dominates globally since the Industrial Revolution. The linear model, heavily resource intensive and fossil fuels driven, is not sustainable anymore because natural resources are limited and environmental pollution has reached levels never achieved before, causing irreversible damage to the Planet. The circular economy stands as a new growth model that is restorative and regenerative by design and aims to increase the efficiency of resource use, to keep products, components, and materials at their highest utility and value at all times, and to eliminate waste. The transition towards a circular economy can bring significant benefits to businesses, the environment, and to society. Disruptive technologies introduced by the Industry 4.0 can help companies in this transition and be the basis for a sustainable operations management.

This study represents a contribution to the integration of the increasingly popular and largely separate topics of Industry 4.0 and circular economy. Despite the extensive literature available concerning the two themes, few works deal with the potential of Industry 4.0 applications to achieve a circular economy. The aim of the study is to investigate how I4.0 technologies can support companies in implementing circular economy principles.

FIRST CHAPTER – CIRCULAR ECONOMY: THE CONCEPT – The first chapter provides a literature overview on the circular economy concept, its fundamental principles, and the different schools of thought from which it originates. Moreover, it illustrates the policies that the European Union has adopted in order to foster the transition into circular economy. Finally, it examines the relevance of the CE approach for achieving the Sustainable Development Goals.

SECOND CHAPTER – CIRCULAR ECONOMY AND INDUSTRY 4.0 – The second chapter describes the major features of the Industry 4.0 and its enabling technologies. First, great emphasis is given to the Cyber-Physical Systems (CPSs), Internet of Things (IoT), big data and analytics, cloud computing, as well as additive manufacturing, simulation, augmented reality, artificial intelligence, autonomous robots, and horizontal and vertical system integration. Afterwards, through a literature analysis, the chapter investigates how and which I4.0 technologies can help firms to meet the CE principles of Reduce and "Design out waste and pollution", Reuse and "Keep products and materials in use", Recycle, and "Regenerate natural systems".

THIRD CHAPTER – SMART GREEN FACTORY – The third chapter explores the concepts of smart factory and green factory. In particular, it analyses the benefits and challenges of a firm that decides to adopt simultaneously the Industry 4.0 and circular economy approaches becoming a Smart Green Factory. Furthermore, it provides a roadmap for manufacturing industries on how they should move toward sustainable operations and achieve CE objectives.

FOURTH CHAPTER – ANALYSIS OF CIRCULAR ECONOMY AND INDUSTRY 4.0 IN ITALY – The fourth chapter examines real cases of Italian manufacturing companies which practice circular economy and which have been classified as "Excellence in the circular economy" by Confindustria; it analyses the circular economy project undertaken by each firm and the technologies adopted. The aim is to investigate if, and if so how, the Industry 4.0 technologies support the implementation of the circular economy projects and, more widely, the fundamental principles of the circular economy. The results emerged from the empirical research are then compared with those arisen from the literature analysis.

CHAPTER 1
CIRCULAR ECONOMY: THE CONCEPT

1.1 There is an urgent need to act to save our Planet

Nowadays one of the world's most pressing challenges is the one posed by climate change. The European Environment Agency reported that last decade was the warmest on record. Global average annual temperature was 0.91 °C to 0.96 °C warmer than pre-industrial average[1]; in Europe these numbers rise to 1.6 °C to 1.7 °C. Climate models project further increases in global average temperature over the 21st century, at least between 0.3 °C and 1.7 °C in the lowest emissions scenario. Starting with the end of the 19th century records show long-term warming trends. They have been most rapid since the 1970s with an average increase of 0.1°C every five to six years (European Environment Agency [EEA], 2019a).

Extreme weather events, such as floods, droughts, storms, and heatwaves, environmental problems like sea-level rise, and biodiversity loss are all possible consequences of a changing climate that could threaten the integrity of the natural ecosystems essential for humanity's survival.

Global economic damage corresponding to a 1.5 °C rise above the pre-industrial levels has been estimated at USD 54 trillion in 2100, increasing to USD 69 trillion with a 2 °C rise (Ellen MacArthur Foundation [EMF], 2019b).

The global warming is attributed to human emissions of greenhouse gases (GHG), namely carbon dioxide (CO_2), nitrous oxide, methane, and others. Today CO_2 concentrations in the atmosphere are well over 400 ppm (parts per million), their highest levels in over 800.000 years. In fact, over this period there were fluctuations in CO_2 concentrations, but the level has never exceeded 300 ppm. The increasing trend has been driven by the Industrial Revolution that generated a rise of human emissions of CO_2 from burning fossil fuels. Global CO_2 levels rose rapidly over the past few centuries, in particular in the recent decades, increasing the

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[1] All data sets show warming compared with pre-industrial temperatures using the earliest observations from the period 1850-1900 as a proxy.

level of carbon dioxide emissions from 2 billion tonnes in 1900 to over 36 billion tonnes today (Ritchie & Roser, 2020).

Currently, approximately 80% of global energy consumption is maintained by extracting fossil fuels that comprise oil, gas, and coal. The extractive industries account for half of the global CO_2 emissions and more than 90% of biodiversity loss (Hussain et al., 2020). Because of enormous economic growth, over the past 50 years the consume of natural resources has more than tripled; humans are using natural resources 1.75 times faster than ecosystems can regenerate[2]. Depletion of resources is an undisrupted fact. Assuming that the fossil fuels extraction will remain at the early 1990s level, the raw material reserves should be exhausted as follow: oil within 40 years, natural gas 60 years and coal 197 years (Bulkowska et al., 2016). If humans do not change their way of operating and do not start to switch to other sources of energy, emissions will continue, the planet will keep warming, and resources will use up, compromising the possibilities for future generations.

Data show that a strong intervention is needed in order to reduce emissions and natural resources consumptions, before the situation becomes irreversible.

1.2 From a linear to a circular model

1.2.1 The linear model: an unsustainable practice

The GHG emissions causing climate change are the result of the dominant economic development model, the so called “take, make and dispose” linear model (Ghisellini et al., 2016). The approach is heavily extractive and resource intensive; it relies on fossil fuels and doesn’t manage resources such as land, water, and minerals for the long term, thus resulting in a large production of damaging greenhouse gases (EMF, 2019b).

Starting from the First Industrial Revolution, global economy has been based on the linear model ─ also defined “cradle to grave” ─ in which the lifecycle of goods starts from the extraction of raw materials, continues with the processing/production, followed by consumption, and ends with the disposal of waste and of the products themselves which have become refuse. The linear model, based on the cost-efficient production of goods, is still prevailing today. The availability of relatively cheap and abundant natural resources and energy, and a wide range of technological and social innovations ─ including engines, electricity, and assembly lines for the mass production of goods ─ are some of the drivers that

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[2] https://theconversation.com/resource-depletion-is-a-serious-problem-but-footprint-estimates-dont-tell-us-much-about-it-120065

propelled this model to dominance (EEA, 2017). In addition, design life-limited products represents for companies a way to obtain higher level of sales.

With the "take, make and dispose" linear model, people surround themselves with objects that they use only for a limited time and the resources, which are extracted from the planet Earth to make these objects, are used one or twice and then dumped[3].

Figure 1 – The Linear Model

Source: Ellen MacArthur Foundation's website[4]

Even today our model of economic growth continues to be largely based on the intensive use of natural resources. However, the resources on our Planet are non-renewable and finite — except for rainfalls, sunlight, biomass, animals, and people — so the present linear industrial economy is unsustainable over time.

1.2.2 The need to move towards a Circular Economy

The current resource-intensive model hits not only the Earth, which is deprived of its resources and polluted by GHG emissions and the creation of large waste dumps, but will also hit directly our economies and societies, failing to generate prosperity for the future. In fact, if humans do not appreciate the crucial role that natural capital places on their economic success, they under-manage it and impair the Planet's ability to regenerate itself providing natural capital for future generations.

Therefore, we need to find a more intelligent resources use, which gives the possibility to reuse them and create more from less. One way to do this is the circularity, so imitate nature where everything — water, biomass, CO_2, seasons — works in cycles, waste free. So, we have to switch to a Circular Economy (CE) in which "natural systems are regenerated, energy is from renewable sources, materials are safe and increasingly from renewable sources, and

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[3] https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy

[4] https://www.ellenmacarthurfoundation.org/

waste is avoided through the superior design of materials, products, and business models" (EMF, 2019b).
The CE requires a fundamental shift in the way the economy functions and creates value: we have to change how we manage resources, how we make and use products, and what we do with the materials afterwards.

The problem of limited resources is destined to become increasingly serious due to the exponential growth of the population (Giorgi et al., 2017); since 1950, the world population has tripled to 7.5 billion and it is projected to grow to 9.7 billion in 2050 and 10.9 billion in 2100 (United Nations Department of Economic and Social Affairs [UNDESA], 2019). Globally, resource use could double by 2060, with water demand increasing 55% by 2050, and energy demand up 30% by 2040 (Organization for Economic Co-operation and Development [OECD], 2012; International Energy Agency [IEA], 2017; International Resource Panel [IRP], 2019).

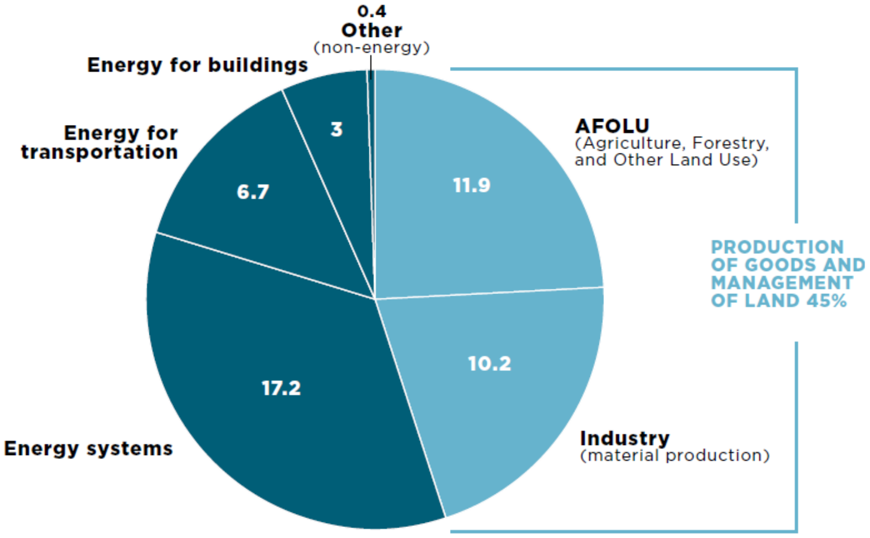
Literature has focused on the respect for the limits of the planet's resources and the reduction of the damages caused to the environment since the mid-1960s. In 1966, in his work *The economics of the coming spaceship earth*, the economist Kennet Boulding discussed the theme of the scarcity of resources. In the work he contrasted two different types of economy: the "cowboy" and the "spaceship" economy. The cowboy symbolizes illimitable plains and he is used by the author to describe an economy based on the behaviour of reckless individuals who plunder natural resources considering them unlimited. This view is opposed to the "spaceship economy" in which people have to survive with restricted reserves, conserve and reuse material and energy, like astronauts aboard an orbiting capsule. Boulding stated that until his time economy had been an open economy, or "cowboy economy", but the future economy would have to be a closed economy, or "spaceship economy". He was one of the first to argue the need for the economic system to fit itself to the ecological system with its limited resources. According to Boulding, people had to change their mind-sets and see the Earth as "a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, people must find their place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy" (Boulding, 1966).

The considerations of the author about the need to harmonize economic growth with a fair consumption of resources have set the basis for the development of new concepts concerning environmental economics such as bioeconomy, sustainable development, ecological economy, green economy and circular economy (Conti & Ciasullo, 2016).

1.2.3 The Circular Economy: a tool to tackles climate change

To date, the transition to renewable energy has been used as the main tool to tackle climate crisis: generation of electricity from sunlight, wind, water, and geothermal heat has increasingly substituted fossil fuel alternatives. However, decarbonisation of the energy system can only address 55% of global GHG emissions. The main challenge today is to drive down the remaining 45%, the harder-to-reduce emissions, that is associated with the production of goods and land use, such as deforestation (Figure 2).

Figure 2 – Global GHG emissions. Billion tonnes of CO_2 per year, 2010[5]



Source: EMF (2019b)

To achieve this goal humans need to move away from today's linear model towards an economy that is regenerative by design: the circular economy. Reduce, reuse, recycle as well as design out waste and pollution, keep products and materials in use, and regenerate natural systems are the foundations of this new economy. The application of these principles may have important impact on the current environmental situation since it will permit to reduce

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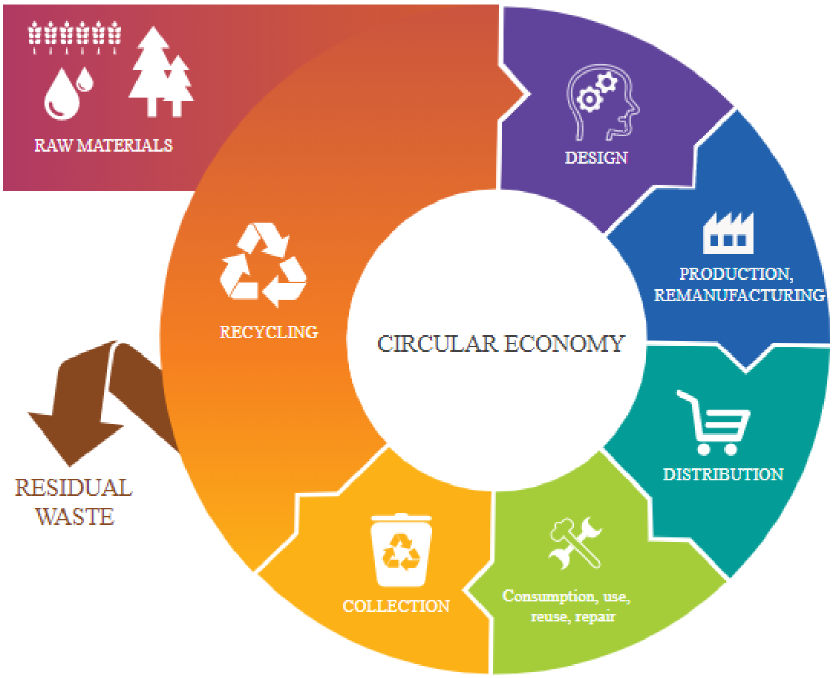
[5] "Industry" and "AFOLU" include their own energy-related emissions but not indirect emissions from electricity and heat production. "Energy systems" refers to the production of electricity and heat as well as fuel extraction, refining, processing, and transportation.

GHG emissions across the value chain, retain the embodied energy in products and materials, and increase carbon sequestration. The Ellen MacArthur Foundation, the world's leading organization for the promotion and development of circular economy[6], found that this different way to operate could reduce GHG emissions by 22-44% in 2050 compared to the current development path. Therefore, if applied to the whole economy, CE strategies can represent a great help to tackle climate change (EMF, 2019b). Each of the CE principles will be presented in more detail later.

Figure 3 – The Circular Economy



Source: European Union's website[7]

1.3 Literature overview

1.3.1 Circular Economy definition

The circular economy concept has gained momentum since the late 1970s (Geissdoerfer et al., 2017). It comes from different epistemological fields and there is still a lack of consensus on terminologies and definitions in literature (Homrich et al., 2018).

Kirchherr et al. (2017), analysing peer-reviewed journals as well as works that are not peer-reviewed, identified 114 circular economy definitions. Geng and Doberstein (2008) affirmed

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[6] The Ellen MacArthur Foundation is a UK private foundation established in 2010.

[7] https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

that CE consists in the “realization of [a] closed loop material flow in the whole economic system”; similarly, Bocken et al. (2016) defined it as “design and business model strategies [that are] slowing, closing, and narrowing resource loops”. Webster (2015) stated that “a circular economy is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times”.

Table 1 – Some of the CE definitions

Reference	CE definition
Bocken et al. (2016)	Design and business model strategies that are slowing, closing, and narrowing resource loops.
Ellen MacArthur Foundation (2019b)	An economy in which natural systems are regenerated, energy is from renewable sources, materials are safe and increasingly from renewable sources, and waste is avoided through the superior design of materials, products, and business models.
Geissdoerfer et al. (2017)	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.
Geng & Doberstein (2008)	CE has the potential to overcome current environmental and resource management problems while achieving improvements in resource productivity and eco-efficiency. CE is normally understood to mean the realization of a closed loop of materials flow in the economic system.
Su et al. (2013)	CE is a sustainable development strategy aiming to improve the efficiency of materials and energy use. CE is a sustainable development strategy proposed by the central government of China, aiming to improve the efficiency of materials and energy use. CE can be defined as an economy type with a closed-loop of material flows, which is opposite to the traditional open-ended economy.
Webster (2015)	CE is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times.
Zhu et al. (2010)	Due to resource scarcity and environmental degradation, a new development concept emphasizing environmental concerns, called the circular economy.

Source: adapted from Homrich et al. (2018)

Several authors, like Andersen (2007), Su et al. (2013), and Ghisellini et al. (2016), attributed the introduction of the CE term to Pearce and Turner (1989). In their *Economics of Natural Resources and the Environment*, the two authors analysed the relationship between economy and environment and presented the four economic functions of the environment[8] within the context of CE (Andersen, 2007). The British environmental economists investigated the characteristics of the linear contemporary economic system that ignores waste: natural resources are used as inputs for the production of goods and capital goods with the final aim of creating utility, or welfare, from their consumption. In this model environment is considered a *resource supplier*, that provides inputs for production and consumption, and a sink for outputs in the form of waste.

Also the natural system generates waste, but unlike the economic system, the former recycles its waste. In nature there are no landfills: one species waste is another's food, thanks to the energy provided by the sun things grow, then die, nutrients return to the soil safety, and the cycle restarts[9].

Considering waste and the possibility to recycle them, the linear model can be turned into a circular model in which resources are captured, recovered, reused, reinforced and repurposed. In this context the environment works, not only as *resource supplier*, but also as *waste assimilator*, able to absorb the residuals of the economic activity and to transform them into useful resources. In addition, environment is an *amenity provider* that gives pleasures to humans without interference from the economic system, for example through the beauty of landscapes or the existence value of particular species. People may attribute to species some value in relation to human welfare and experience a loss if conditions for species deteriorate. The integrity of the environment is a necessary condition for human and non-human survival, so the environment has also a fourth economic functions, it works as a *life supporter* (Pearce & Turner, 1989).

Although not using the term circular economy, a lot of different authors had already introduced the concept even before Pearce and Turner (1989). In his 1971 book *The Closing Circle*[10], Commoner underlined the need for the US economy to transform and conform to the

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[8] Basing on an anthropocentric approach, the neoclassical environmental economic emphasizes the utility of the environment for humans, measured in term of economic welfare. According to this perspective, environment has four welfare economic functions: a resource base for the economy, an amenity values, a sink for residual flows, and a life-support system (Andersen, 2007).

[9] https://www.ellenmacarthurfoundation.org/circular-economy/concept

[10] Barry Commoner, in his book *The Closing Circle,* defined four laws of ecology:

rigid laws governing nature, in which there is no waste ("Everything must go somewhere", second law of ecology). Human beings have often built their well-being at the expense of the planet's natural resources and inevitably, sooner or later, will have to pay the price ("There is no such thing as a free lunch", fourth law) (Egan, 2007).

In 1976, in *The Potential for Substituting Manpower for Energy,* a report to the European Commission, Stahel and Reday-Mulvey conceptualized a loop economy in which goods, once used, are turned into resources for others and waste are minimized. The service-life of goods, components and materials, is extended through reuse, re-making, repair, re-manufacturing and technological upgrading. As Stahel later affirmed, the underlying logic is "reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture[11] what cannot be repaired" (Stahel, 2016). The authors found that energy consumption in manufacturing is mainly related, not to the actual manufacturing process, but to extraction and processing of resources and that by reusing products, rather than producing new ones, labour would replace energy with positive effect such as job creation and energy savings[12]. Moreover Stahel, in 1982, dealing with business models, claimed that selling utilizations, instead of ownership goods, is the most suitable model for a loop economy (Geissdoerfer et al., 2017).

In the very last few years, CE is receiving increasing attention from both scholars and practitioners. From an analysis of Geissdoerfer et al. (2017) it emerged that only 30 articles were published on CE in 2014, but this number grew to 100 in 2016[13].

- *Everything is connected to everything else*. The environment is a living machine, huge and extremely complex, each living organism is connected with many others and what affects one, affects all.
- *Everything must go somewhere*. In any natural system, what is eliminated by one organism as waste is used by another as food, nothing disappears.
- *Nature knows best*. Humans cannot exploit nature as they like. If nature rebels man collapses.
- *There is no such thing as a free lunch*. There is no gain that can be obtained without a certain cost: exploitation of nature will inevitably involve the conversion of resources from useful to useless forms.

[11] Remanufacturing is a form of a product recovery process by which a previously sold, worn, or non-functional product or component is returned to a "like-new" or "better-than-new" condition and warranted in performance level and quality. The product is rebuilt to specifications of the original manufactured product using a combination of reused, repaired, and new parts. Remanufacturing is considered as one of the product life extension strategies of a circular economy to keep a product or component at its highest utility and value (Charnley et al., 2019).

[12] https://ec.europa.eu/environment/ecoap/about-eco-innovation/experts-interviews/reuse-is-the-key-to-the-circular-economy_en

[13] They collected data about the number of reviews and articles per year with the topic circular economy on Web-of-Science.

1.3.2 The different schools of thought

The contemporary circular economy model cannot be traced back to one single author, but synthesises several schools of thought sharing the idea of closed loops, including the Cradle to Cradle, Performance Economy, Biomimicry, Industrial Ecology, Natural Capitalism, Blue Economy, and Regenerative Design[14].

1.3.2.1 Cradle to Cradle

The development of the concept Cradle to Cradle is due to the work of the German chemist Michael Braungart and the American architect Bill McDonough. The authors argued that human beings must learn to imitate the “biological metabolism”, that is, that of the cycles of nature, in which the concept of waste itself does not exist. This metabolism must be the model for developing the second type of metabolism present on our Planet: the “technical metabolism”, that is, that of industrial cycles. Recycle, reduce, and reuse is not enough; to eliminate the concept of waste, each product must be designed from the beginning ─ design phase ─ based on the principle that waste doesn’t exist. The design philosophy, conceived by the two authors, considers all material involved in industrial and commercial processes to be nutrients for the two metabolisms. The products must be designed in such a way as to be composed of biodegradable materials that become food for biological cycles ─ biological nutrients ─ or of technical materials ─ technical nutrients ─ which remain within closed technical cycles, circulating continuously as valuable nutrients for the industry (McDonough & Braungart, 2002). For example, technological products, which are subjected to frequent updates, must be designed so that their components’ disassembly and recovery are easy, aiding reutilization of individual parts for the next generation.

1.3.2.2 Performance Economy

Walter Stahel, architect and industrial analyst, is considered one of the founding fathers of circular economy. He is credited with having coined the expression “Cradle to Cradle”. In 2010, the author introduced the concept of Performance Economy moving attention towards the theme of servitization. Firms have to change their business model moving from selling products to providing services, to sell performances. Manufacturers retain the ownership of products and sell to customers the service of their products for a defined period of time. This model gives relevant benefit to customers who can have a flexible access to goods at a fixed prices per unit used. In part, the current economy is already a performance economy;

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[14] https://www.ellenmacarthurfoundation.org/circular-economy/concept/schools-of-thought

whenever people take a taxi or book an airplane flight, what they are buying is the use of the object, not the object itself. After using the product, the consumer returns it to the manufacturers that uses the old model's materials for new products. This model allows to internalize the responsibility for production costs, risks and waste, and enables entrepreneurs to achieve a higher competitiveness with greatly reduced resource consumption (Stahel, 2010).

1.3.2.3 Biomimicry

The Biomimicry, by Janine Benyus, is a discipline that studies and imitates biological process present in nature as a source of inspiration for the improvement of human activities and technologies. Organisms and ecosystems have to inspire industrial designers and be the base for what the author called "innovation inspired by nature" (Benyus, 1997). The underlying idea is that learning from nature means to access to 3.8 billion years of research and development, in which the Planet has understood what works and what not (Pawlyn, 2019). Biomimicry relies on three key principles:

- Nature as *model*. Mimic nature's forms and processes to cope with human problems.
- Nature as *measure*. Use an ecological standard to judge the sustainability of human innovations.
- Nature as *mentor*. View and value nature not according to what we can extract from the natural world, but what we can learn from it.

1.3.2.4 Industrial Ecology

Industrial Ecology (IE) is a research field interested in understanding cyclical resource-use patterns observed in biological ecosystems to use them as a model for designing mature industrial ecosystems (Graedel & Allenby, 1995).

This approach studies material and energy flows through industrial systems with the aims of creating closed-loop processes that imply the elimination of undesirable by-product thanks to the use of waste as an input for other procedures. Industrial ecology attempts to induce balance and cooperation between environmental sustainability and industrial processes. It tries to develop the latter in such a way that minimizes material waste and pollutants according to the Cradle-to-Cradle concept, which can be considered an extension to industrial ecology (El-Haggar, 2010).

IE represents a new approach to the industrial design of products and processes in which an industrial system is viewed not in isolation from its surrounding systems, but in concert with them (Jelinski et al., 1992). Production processes are designed trying to mimic a natural system by conserving and reusing resources, respecting local ecological constraints, and observing their global impact from the outset.

1.3.2.5 Natural Capitalism

Natural Capitalism outlined by Paul Hawken, Amory Lovins and L. Hunter Lovins (2013) represents a criticism of the traditional “industrial capitalism” which just recognises money and goods as capital and neglects natural capital. Industrial capitalism assigns no value to the large stock of natural capital ─ soil, air, water, and all living beings ─ that are employed in economic activities. On the contrary, natural capitalism acknowledges the importance of nature as resources supplier, waste assimilator, and life supporter. Hawken et al. (2013) proposed an approach that protects the biosphere and improves profits and competitiveness at the same time. The final aim is to create a global economy in which business and environmental interests overlap. Four principles underlie the notion of natural capitalism. The first one concerns the increase in natural resources productivity and the lengthen of their availability through radical changes in product design, production, and technology. The second principle states to eliminate the concept of waste by modelling closed-loop production systems biologically inspired, in which every output returns to the ecosystem as nutrient and becomes an input for another manufacturing process. The third principle consists in leaving the traditional “sale-of-goods” business model, where the business aim is to sell more goods more often, and in moving towards a “service-and-flow” model, in which value is created providing continuous services to customers. Finally, the fourth principle considers the need to reinvest profits in the natural capital to restore and expand the amount of valuable natural resources.

1.3.2.6 Blue Economy

Initiated by Gunter Pauli, Blue Economy advocates the emulation of the natural ecosystem in which everything is connected, biodegradable, and evolving towards symbiosis. Nature only works with what is locally available, thus businesses should evolve in this way too, considering their local environment, physical and ecological characteristics.

Natural systems are non-linear, cascade nutrients, matter, and energy, and waste does not exist; therefore the Blue Economy promotes an economy where resources are used in a cascading systems so that the waste of one product becomes the input to create a new cash flow. In his book *The blue economy: 10 years, 100 innovations, 100 million jobs*, Pauli provided the example of a coffee company that organizes production in a way that allows it to generate revenues from three businesses and, concurrently, to avoid creating waste. The production of coffee could represent the first source of income, then the company could use the waste stream from coffee manufacture to cultivate mushrooms. Finally, what is left from the harvest could be employed as animal feed. Moreover, the author suggested the creation of clusters to facilitate the exchange of by-products and fostered the idea to "substitute something with nothing" whenever possible. So, for example, a traditional battery could be replaced not by a green battery, but by an alternative source of energy (Pauli, 2010).

1.3.2.7 Regenerative Design

The idea of Regenerative Design is developed by the American architecture John T. Lyle who extended to all systems the concept of regeneration that had already been formulated earlier for agriculture. In 1980s, indeed, Robert Rodale coined the term "regenerative organic agriculture" to describe a holistic approach to farming that encourages continuous innovation and improvement of environmental, social, and economic measures[15].

The author saw the constant organic renewal of the complex living system as the basis for healthy soil, food, and people. Inspired by Rodale, in 1990s Lyle conveyed the idea of regenerative systems for all other aspects of the world. The Regenerative Design represents a system of technologies and strategies, based on an understanding of the inner working of ecosystems, that generates designs to regenerate, rather than deplete, underlying life support systems and resources. Human being and anthropized environment exist within natural systems and, therefore, the human context should be designed to co-evolve with these systems. People have not only to estimate the environmental, social, and economic impact of what they design, but also consider the relationship between them and nature to create a resilient and lush ecosystem. According to Lyle, durable and responsible designs can emerge by designers who have understood ecological order operating and link this knowledge to human values. He believed that at the core of the growing environmental degradation and resource depletion there was the crudity of the design of the 20th Century landscape. While nature evolves adapting to local conditions, humans have designed relatively simple patterns and forms to be easily replicable anywhere. Nature follows cyclical flows, cycling and recycling all materials and energy, on the contrary, human has adopted linear flows from source to sink (Mang & Reed, 2012). The author illustrated a set of principles for a design technology that is able to move away from the source-to-sink one-way flows, that is

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[15] https://rodaleinstitute.org/why-organic/organic-basics/regenerative-organic-agriculture/

degenerative, and implement cyclical flows at resources, consumption centers, and sinks. This new regenerative system provides for continuous replacement, through their own functional processes, of the energy and materials used in their operations (Lyle, 1996).

1.4 The principles of the Circular Economy

Circular economy is governed by the so called 3R Principles: Reduce, Reuse, and Recycle (Preston, 2012; Su et al., 2013; Ghisellini et al., 2016; Kirchherr et al., 2017).

China and European countries have set the 3R framework at the core of their CE policies. More specifically, the CE Promotion Law of the People's Republic of China defined CE "a generic term for the reducing, reusing and recycling activities conducted in the process of production, circulation and consumption"[16].

The Reduce principle aims to minimize the input of primary energy, raw materials, and waste through the improvement of production efficiency, the so called eco-efficiency. At the same time, a similar enhancement is encouraged also in the consumption processes. Introducing better technologies, more compact and lightweight products, simplified packaging, and a simpler lifestyle are just examples of what can contribute in pursuing these goals. Eco-efficiency in production processes can be reached by means of two interventions: maintaining or increasing the value of products, and simultaneously, reducing their environmental impact. The former requires to use fewer resources per unit of value produced, and the latter to replace harmful substances with safer ones (Ghisellini et al., 2016).

The Reuse principle refers to "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (European Union [EU], 2008). According to this principle, the product as a whole, or its components, are used again after its first life-cycle, for subsequent life-cycles. For instance, by-products of one firm could become resources for other companies allowing to use them to their maximum capability (Su et al., 2013). Reuse generates great environmental benefits since it implies the employment of less resources, energy, and labour compared to the manufacturing of new products from virgin resources (EMF, 2013). Prendeville et al. (2014) underlined that the success of the Reuse principle is tied to some conditions. First, the desire to buy reused products must take hold among consumers, so that demand for these goods increases. Second, it is necessary to intervene on the design of the products for them to last multiple cycles of use

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[16] Circular Economy Promotion Law of the People's Republic of China.

and, finally, companies must be incentivized to take back products and to advertise remanufactured goods.

The Recycle principle is about the recovery of waste that are reprocessed into products and materials for the original or other purposes (EU, 2008). Recycling has a positive impact on the environment as it reduces the need for operations ─ extracting, refining, and processing raw materials ─ which generate greenhouse gas emissions. Furthermore, if society is able to benefit from still usable resources, recycling all its waste, the need for landfills would be eliminated.

In addition to the 3R principles, in its 2008 Waste Framework Directive, the European Union considered also a fourth R, Recover, defining it as "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" (EU, 2008).

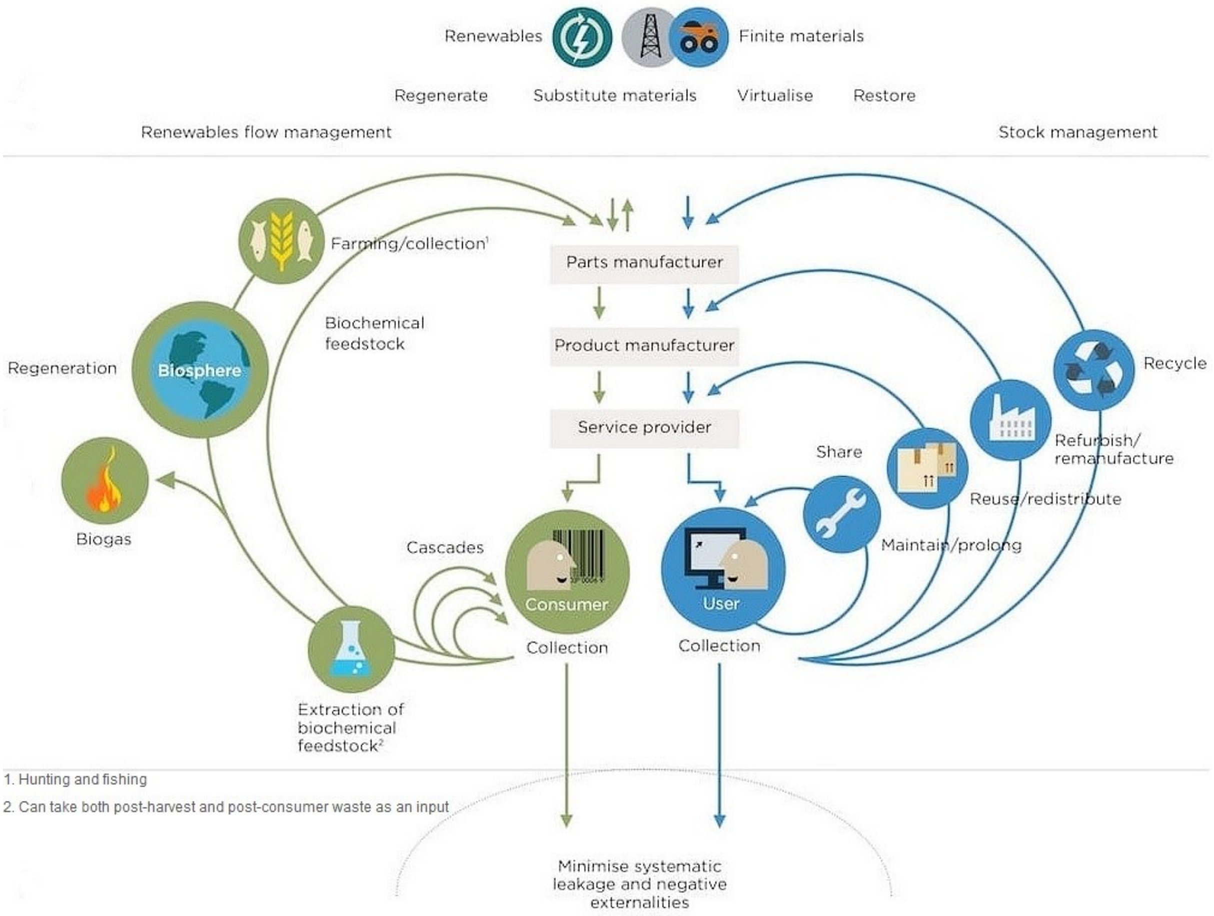
The 3Rs can be integrated by three additional principles developed by the Ellen MacArthur Foundation (Ghisellini et al., 2016).
The first one, "Design out waste and pollution", is grounded on the idea that waste and pollution are not accident, but largely, a result of the way we design things. Therefore, the design phase represents a crucial unit of analysis for the environmental impact reduction of economic activities. Products and materials must be conceived from the outset to be kept in use and/or regenerate natural systems, ensuring waste is not created in the first place. CE requires goods to be designed for disassembly, modularity, reparability, biodegradability, and to enable reuse, remanufacturing, or regeneration. For instance, nowadays plastic bottles used in beauty and home cleaning are destined for landfill after just a short single-use. If "refill" bottle designs and models were to be applied to all these bottles, packaging and transport savings would represent an 80-85% reduction in GHG emissions compared to today.

The second principle introduced by the CE promoter Foundation, "Keep products and materials in use", concerns the preservation in the economy of the embodied value in products (e.g. energy, labour, and materials). This principle, in line with the first one, requires to develop products and components so they can be reused, repaired, and remanufactured extending the product's lifetime. In fact, the more a product is utilized, the larger the saving in term of resources needed to create a new one, and the higher the utilization of resources already contained into the product, such as material, energy, and labour. Keeping products and material in use allows also to reduce GHG emissions as it avoids emissions associated with the production of new goods. As well as reusing products, recirculating materials is another strategy that can be pursued to preserve value embedded in products. Recycling activities, indeed, need much less energy than the production of virgin materials. As an example, steel recycling uses 10-15% of the energy required in the production of primary steel. The positive effects of recycling are also evident with regard to emissions; for example recycling 1 tonne of plastics reduces CO_2 emissions by on average 2 tonnes compared to producing the same tonne of said material from virgin fossil feedstock.

The third additional principle, “Regenerate natural systems”, aims to enhance natural systems by returning valuable nutrients to the soil. Instead of simply doing less harm, circular economy tries to do good to the environment. It favours the use of renewable resources such as renewable energy, like wind, solar, and biomass, or renewable materials, like wood. For instance, in agriculture, examples of regenerative practices include employing organic fertilizers, crop rotation, and cultivating crop varieties to promote agro-biodiversity. Regenerative methods can contribute to pollution reduction since lower emission can be reached through renewable, low carbon or secondary materials ─ recyclates ─ as alternative inputs to new production. Substituting materials, indeed, reduce GHG emissions and, simultaneously, sequester carbon, resulting in a double positive effect for the environment (EMF, 2019b). An example of renewable material is bamboo. A hectare of giant bamboo, in fact, has the potential to sequester 17 tons of carbon dioxide in a year, and, at the same time, offers the compressive strength of concrete and the tensile strength of steel.

All these principles combined can be illustrated in Figure 4. CE aims to decouple economic growth from the consumption of finite resources focusing on rebuilding economic, natural, and social capital. The system diagram (Figure 4) illustrates the continuous flow of technical and biological materials through the “value circle”. Technical materials, such as metals and plastics, are designed to flow in cycles thanks to strategies like reuse, repair, remanufacture, or recycling. Biological material, instead, such as cotton or wood, can return safely to the system through processes like composting and anaerobic digestion. Biological cycles regenerate living systems, such as soil, which provide renewable resources for the economy.

Figure 4 – Circular economy system diagram



Source: Ellen MacArthur Foundation's website[17]

1.5 Circular Economy in Europe

1.5.1 Circular Economy within the European legislation framework

Nowadays, environmental protection is one of European Union's priority objectives, representing also one of the main challenges that Europe is committed to face. In 1957, the treaties establishing the European Communities[18] didn't provide for any normative form concerning environmental protection. It was not until 1970s that, driven by growing environmental pressures, the European Union recognized the need to establish a common environmental policy. Since 1973, the European Commission has issued multi-annual Environment Action Programmes (EAPs) setting out forthcoming legislative proposals and goals for the EU environment policy (Sequeira & Reis, 2019).

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[17] https://www.ellenmacarthurfoundation.org/circular-economy/concept

[18] In 1957 the Treaties of Rome were signed; the first established a European Economic Community (EEC), the second a European Atomic Energy Community (EAEC or Euratom).

In 2013, the Council and the European Parliament adopted the EU Seventh Environment Action Programme to 2020, entitled “Living well, within the limits of our planet”. This programme is intended to help guide EU action on the environment and climate change for the period up to 2020. However, in order to give more long-term direction, it provides a vision of where it wants the Union to be by 2050: “In 2050, we live well, within the planet’s ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued, and restored in ways that enhance our society’s resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society” (EU, 2013). The vision reflects the recognition that the prosperity, health, and well-being of European citizens are intrinsically linked to a new economy that becomes circular.

In support of the ambitious vision for 2050, and the specific targets to be achieved by 2020, the EU implemented a range of policy packages. In 2015, the European Commission launched its first Circular Economy Package, which contains revised legislative proposals on waste to stimulate Europe’s transition towards a circular economy with the aim to boost global competitiveness, foster sustainable economic growth, and generate new jobs.

While the previous 2014 communication, “Towards a circular economy: A zero waste programme for Europe” (COM 398)[19], was focused just on waste reduction, the “Closing the loop ─ An EU action plan for the Circular Economy” (COM 614) represented a concrete and ambitious programme which considered the whole economic cycle. Its measures, indeed, spanned from production and consumption to waste management and the market for secondary raw materials.

The COM 614 underlined that the design phase has an important impact on sourcing, resource use, and waste generation throughout a product’s life and how a better design can make products more durable or easier to repair, upgrade, or remanufacture. It promoted innovative forms of consumption, like sharing products or consuming services rather than goods, as well as innovative industrial processes, such as industrial symbiosis that allows waste or by-

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[19] The COM 398, “Towards a circular economy: A zero waste programme for Europe”, focused on “designing out” waste, stressed the need to invest in innovation throughout the value chain, rather than relying solely on solutions at the end of life of a product. For instance, companies could have found ways to decrease the quantity of materials needed to produce goods, or reduce the use of materials that are difficult to recycle, or creating markets for secondary raw materials. European commission showed as all these interventions could have generated positive effect not only to the environment, but also to the European economy (EC, 2014).

products of one industry to become inputs for another. Furthermore, the communication highlighted the need to put into practice the EU waste hierarchy established by the previous directive 2008/98/CE[20]. The EU waste hierarchy establishes a priority order from prevention, preparation for reuse, recycling and energy recovery through disposal, such as landfilling, and aims to encourage the options that deliver the best overall environmental outcome.

In addition, in the COM 614 the European Commission identified 5 priority areas which needed to be addressed in a targeted way since they faced specific challenges in the context of circular economy. This could be due to the specificities of their products or value-chains, their environmental footprint, or dependency on material from outside Europe. These sectors were plastics, food waste, critical raw materials, construction and demolition, and biomass and bio-based products (European Commission [EC], 2015).

The 2015 CE package included also an EU Action Plan for the Circular Economy setting out a number of initiatives aiming at closing the loop of product lifecycles, primarily through greater recycling and re-use. Three years after adoption, the Plan was fully completed. Its actions have been implemented, even if the work on some of them is continuing[21].

In 2018, the European Commission adopted complementary measures in its 2018 Circular Economy Package proposing new waste-management targets regarding reuse, recycling, and landfilling, strengthening provisions on waste prevention and extended producer responsibility, and streamlining definitions, reporting obligations and calculation methods for targets. Among the new objectives, the package includes two common EU targets: recycling at least 55% of municipal waste and 65% of packaging waste by 2025. These targets would rise to 60% and 70% by 2030 respectively[22].

Recently, in her November 2019 statement to the European Parliament, the President-elect Ursula von der Leyen outlined six European Commission's priorities for the period 2019-2024[23]. One of these is represented by an ambitious European Green Deal that aims to make

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[20] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

[21] https://ec.europa.eu/environment/circular-economy/first_circular_economy_action_plan.html

[22] https://www.europarl.europa.eu/news/en/headlines/society/20170120STO59356/the-circular-economy-package-new-eu-targets-for-recycling

[23] The main political guidelines of the European Commission are brought together under six broad headings: "A stronger Europe in the world", "A European Green Deal", "A Europe fit for the digital age", "An economy that

Europe the first climate-neutral continent by 2050. The President defined the programme as a "new growth strategy, for a growth that gives back more than it takes away" (EC, 2019).

The Green Deal stands as a roadmap for making the EU's economy sustainable by turning climate and environmental challenges into opportunities across all policy areas.

On 11 December 2019, the Commission adopted a communication on the European Green Deal that sets out a detailed vision to achieve the challenging goal for 2050, safeguard biodiversity, establish a circular economy, and eliminate pollution (European Parliamentary Research Service, 2020).

One of the adopted policies is the increasing of the EU's climate ambition for 2030, necessary to be able to reach the final aim of climate neutrality. Previous measures have already led to important results: between 1990 and 2018, indeed, the EU reduced greenhouse gas emissions by 23%, while the economy grew by 61% in the same period. Nevertheless, those policies will only reduce greenhouse gas emissions by 60% by 2050. Therefore, the European Commission rose the EU's greenhouse gas emission reductions target for 2030 to at least 50% compared with 1990 levels in a responsible way.

A new Circular Economy Action Plan is one of the main blocks of the European Green Deal. It includes a "sustainable products" policy to support the circular design of all goods based on a common methodology and principles. Reducing and reusing materials are prioritized before recycling them. New business models are fostered to boost sorting, reuse, and recycling and minimum requirements are set to prevent environmentally harmful products from being placed on the EU market. The new Circular Economy Action Plan aims to ensure that the resources used are kept in the EU economy for as long as possible[24]; action focus in particular on resource-intensive sectors such as textiles, construction, electronics, and plastics.

As an example, among the different Green Deal's objectives, there is the development of requirements to ensure that all packaging in the EU market is reusable or recyclable in an economically viable manner by 2030. Furthermore, the European Commission boosts the creation of a regulatory framework for biodegradable and bio-based plastics, and will implement measures on single use plastics (EC, 2019).

Meeting the objectives of the European Green Deal will require significant investment from both the EU and the national public sector, as well as the private sector. On January 2020, the Commission presented "The European Green Deal Investment Plan and Just Transition

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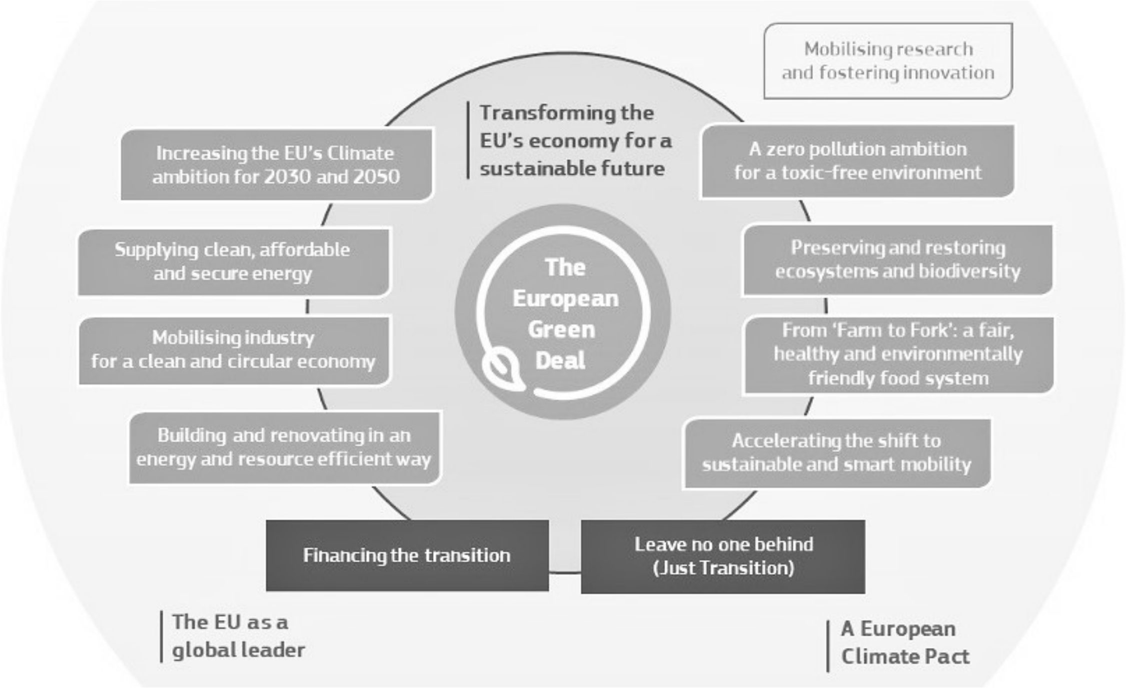
works for people", "A new push for European democracy", and "Promoting the European way of life". Together they define the framework within which the Commission will act up to 2024.

[24] https://ec.europa.eu/environment/circular-economy/

Mechanism” to finance the green transition. The Plan will mobilise public investment and help to unlock private funds through EU financial instruments which would lead to at least €1 trillion of investments[25].

Figure 5 – The European Green Deal



Source: EC (2019a)

With the 7th EAP that was coming to its end, in October 2019 the Council adopted conclusions which offer political guidance for the EU’s environment and climate change policies for the period 2021-2030 and it called upon the Commission to present the following year a proposal for an 8th Environment Action Program[26].

1.5.2 Circular Economy benefits in Europe

Environmental policies adopted by EU, in particular those on CE, brought important benefits in term of employment, innovation, resource efficiency, cost savings, and productivity.

The EU Monitoring Framework for the Circular Economy showed that the first Circular Economy Action Plan, adopted by the Commission in 2015, has generated positive effects in term of job creation and open up of new business opportunities. In 2016, sectors relevant to CE employed more than four million workers, a 6% increase compared to 2012, and new

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[25] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_17

[26] https://www.consilium.europa.eu/en/press/press-releases/2019/10/04/8th-environmental-action-programme-council-adopts-conclusions/

business models and markets rose thanks to circularity. Circular activities, such as repair, reuse or recycling, generated almost €147 billion in value added in 2016 while standing for around €17.5 billion worth of investments (EC, 2019).

The COM 398 stated that resource efficiency improvements all along the value chains could reduce material inputs needs by 17%-24% by 2030, with a consequent savings potential of €630 billion per year for the European industry.

Furthermore, some CE practices, such as waste prevention, ecodesign, and reuse, could bring net savings of €600 billion, or 8% of annual turnover, for businesses in the EU, while reducing total annual greenhouse gas emissions by 2-4% (EC, 2014).

The Ellen MacArthur Foundation estimated that by 2030, a shift toward a CE could improve resource productivity in the EU by up to 3% annually and generate an annual net benefit of €1.8 trillion (EMF, 2015).

1.6 Circular Economy and Sustainable Development

Sustainable development is defined by the Brundtland report[27] in 1987 as a "development that 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).

It provides a comprehensive approach bringing together economic, social, and environmental considerations.

1.6.1 The 2030 Agenda

The sustainable development concept is the basis of the United Nations' 2030 Agenda, adopted by world leaders in 2015. The 2030 Agenda sets out 17 Sustainable Development Goals (SDGs) and 169 associated targets applies to all countries at all levels of development, taking into account their capacities and circumstances. SDGs concern human dignity, regional and global stability, a healthy planet, fair and resilient societies, and prosperous economies[28]. Many SDGs embed a strong environmental dimension. In particular, SDG 12 promotes

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[27] In 1987 the World Commission on Environment and Development (WCED) drafted the report *Our Common Future*, also called Brundtland report in recognition of Gro Harlem Brundtland, chairperson of the Commission. In the document, besides to define the concept of sustainable development, the Commission argued that environmental protection and sustainable development should have become an integral part of the mandates of all governmental bodies, international organizations, and large private sector institutions (World Commission on Environment and Development, 1987).

[28] https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals/eu-approach-sustainable-development_en

responsible consumption and production, SDG 13 fosters climate action, and SDG 14 and 15 aim to advance the conservation of marine and terrestrial ecosystems and the sustainable use of their resources.

Figure 6 – The Sustainable Development Goals

Source: United Nations' website [29]

In the treaty establishing the European Community ─ Treaty of Lisbon of 2007 ─ sustainable development is set as the third main aim of the EU, right after promoting peace and offering EU citizens freedom. The EU has expressed its ambition to play a leading role in implementing the UN's 2030 Agenda. In 2016[30], the European Commission committed itself to integrating the SDGs in both its internal and external policies. This included the mapping of EU policies and actions for each SDG[31] and the publication of an annual monitoring report on the EU's progress towards SDGs. Lately, in January 2019, the EC adopted the reflection paper "Towards a sustainable Europe by 2030"[32] to launch a forward-looking debate on how

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[29] https://www.un.org/sustainabledevelopment/news/communications-material/

[30] EC, 2016, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Next steps for a sustainable European future – European action for sustainability, COM(2016), 739, final.

[31] EC, 2016, Commission staff working document – Key European action supporting the 2030 agenda and the Sustainable Development Goals, SWD(2016), 390, final.

[32] EC, 2019, *Towards a sustainable Europe by 2030*, Reflection paper, European Commission.

to best progress on the SDGs (EEA, 2019b). In addition, the SDGs feature in all of the six European Commission priorities for 2019-24.

1.6.2 The circular model to achieve the SDGs

Circular economy is recommended as an approach to economic growth that is in line with sustainable development (Korhonen et al., 2018; Schroeder et al., 2019). On the contrary, the linear model adopted by the modern economic system, based on extract-produce-use-dump material and energy, is unsustainable.

Specifically, Schroeder et al. (2019) examined the relevance of the CE approach for achieving the Sustainable Development Goals in developing countries. CE practices, indeed, can potentially contribute directly to reach a significant number of SDG targets. Following the CE concept of the European Environment Agency[33], the authors considered among CE practices activities like eco-design, repair, reuse, refurbishment[34], remanufacture, product sharing, industrial symbiosis, waste prevention and waste recycling. In particular, CE is closely related to SDG 12 (Sustainable Consumption and Production). Targets such as “achieve the sustainable management and efficient use of natural resources by 2030” (12.2), or “substantially reduce waste generation” (12.5)[35] are completely in line with what CE aims to do. For instance, the CE practice of reuse can contribute strongly to these objectives since it allows resource efficiency and decreases waste level and pollution — as it avoids the emissions required to create a new products.

However, the authors claimed that CE practices and principles are transversal and their adoption can help the achievement of other SDGs besides the 12th. For example, turning one industrial facility’s waste into resources of another, the so called industrial symbiosis, is an important CE practice that can contribute to several of the SDG targets. These include the 3.9 (“By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination”), 6.3 (“improve water quality by reducing

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[33] “The concept can, in principle, be applied to all kinds of natural resources, including biotic and abiotic materials, water and land. Eco-design, repair, reuse, refurbishment, remanufacture, product sharing, waste prevention and waste recycling are all important in a circular economy” (EEA, 2016).

[34] Refurbishment is classified as circular strategy of product life extension. It shares many similarities with remanufacture. While refurbishment is the process whereby used products are returned to use conditions with a warranty shorter than a newly manufactured product, remanufacturing is an industrial process where used products are restored to useful life with a warranty and quality at least as good as a newly manufactured product (Charnley et al., 2019).

[35] https://sustainabledevelopment.un.org/post2015/transformingourworld

pollution”), as well as the 8.2 (“higher levels of economic productivity through diversification, technological upgrading, and innovation”). The analysis of the authors showed that the application of CE principles can directly contribute to achieving 21 of the targets and indirectly contribute to additional 28 targets. Moreover, it is important to notice that “as much as CE can assist in achieving many SDG targets, SDGs also can help the promotion of CE practices” (Schroeder et al., 2019).

CHAPTER 2
CIRCULAR ECONOMY AND INDUSTRY 4.0

2.1 Introduction

The invention of the steam engine in 1684 kick-started the Industrial Revolution, which hugely has transformed our ability to make things and uncoupled people from nature. In fact, raw materials and energy were seemingly infinite and this gave birth to a still prevailing growth-model based on intensive use of natural resources, favouring natural capital depletion and damaging the Planet[36].

Since the First Industrial Revolution, the rapid pace of technological progress has continued through the Second and the Third Industrial Revolution, up to the Fourth current one, the so called Industry 4.0. If so far industrial evolution has often been accompanied by damage to the environment in which we live, on the contrary, the present Industry 4.0 gives us the immense opportunity to reverse course and have a positive impact on the Planet. The new technologies connected to this revolution, indeed, allow us to transform the way we do business and to create value in a circular economy, thus enabling to decouple growth and natural resources depletion (World Economic Forum, 2017).

In this chapter it will be analysed how I4.0 technologies can support companies in implementing the CE principles.

2.2 The evolution from the Industry 1.0 to the Industry 4.0

The history has been characterized by four Industrial Revolutions represented by radically new technologies changing the economic systems and how people lived, worked, and related to one other.

The First Industrial Revolution, or Industry 1.0, occurred at the end of the 18th century. It corresponded to the introduction of water- and steam-powered machines which changed

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[36] https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy

dramatically manufacturing, moving from hand-made to machine-made goods. Mechanization allowed an increase in production capabilities making business grow from individual cottage owners to organizations with owners, managers, and employees serving customers (Rao & Prasad, 2018).

Almost a century later, the Second Industrial Revolution began, symbolized by mass production through the use of electric energy. Huge amounts of standardized products were produced using assembly lines and dividing labour among workers, so that each worker did repetitively a part of the total job, allowing to increase productivity. The period between the late 19th century and the early 20th century has been characterized by an unprecedented technological development. Some of the most important inventions in our history were realized in those years: among the many there were the internal combustion engine, automobile, plane, chemical synthesis as well as methods of communication, such as the telegraph and the telephone.

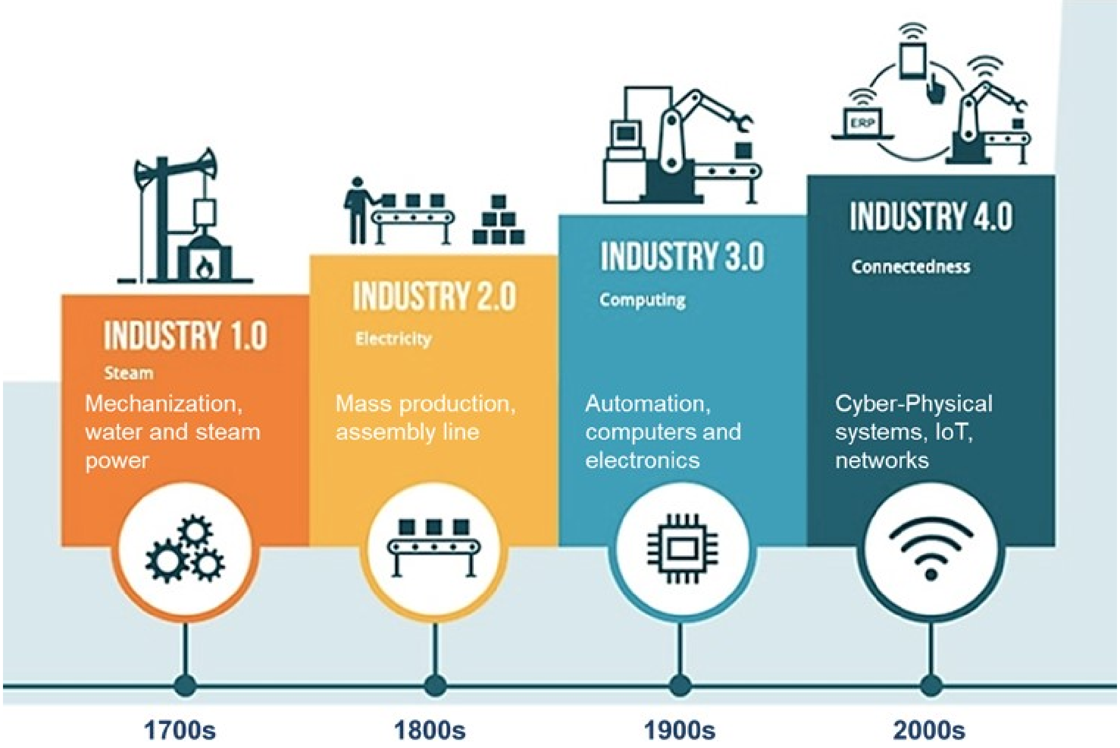
The Third Industrial Revolution started in the second half of the 20th century with the introduction of electronics and IT (Information Technology). It is also called Digital Revolution because it was catalysed by the development of semiconductors, mainframe computing (1960s), personal computing (1970s and 1980s) and Internet (1990s) (Schwab, 2017). Industry 3.0, introducing electronic devices, made it possible to fully automate machines to supplement or replace operators.

Finally, most recently a Fourth Industrial Revolution has built on the Third, thanks to the widespread availability of digital technologies resulting from the latter. Started in 2000s, the Fourth Revolution is characterized by a combination of technologies that are blurring the lines between the physical, digital, and biological spheres, impacting all disciplines, economies and industries (World Economic Forum, 2016).

As the Industry 3.0, also the Industry 4.0 (I4.0) concerns the automation of machines and processes, but differently from the 3.0, it focuses more on the end-to-end digitalization and the integration of digital industrial ecosystems by seeking completely integrated solutions (Xu et al., 2018).

The Figure 7 summarizes the main features of the four Industrial Revolutions.

Figure 7 – Main features of the four Industrial Revolutions



Source: adapted from Automation World[37]

2.3 The Industry 4.0 and enabling technologies

The notion "Industry 4.0" was proposed for the first time by the German federal government in 2011 announcing an initiative named "Industrie 4.0" as one of the key procedures of its high-tech strategy (Hermann et al., 2016).

Industry 4.0 has no single accepted and established definition. The Industrial Internet Consortium defined it as "the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes" (Industrial Internet Consortium, 2013). Koleva (2018) described it as "a set of connected digital technology solutions that support the development of automation, integration and real-time data exchange in manufacturing processes". Moreover, according to Hermann et al. (2016) Industry 4.0 is "a collective term for technologies and concepts of value chain organization".

Shrouf et al. (2014) stated that the core feature of Industry 4.0 is connectivity between machines, employees, suppliers, and customers due to the Internet of Things (IoT) and

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[37] https://www.automationworld.com/factory/iiot/blog/13318945/industry-40what-does-it-mean-to-your-operations#next-slide

electronic devices. Industry 4.0 enables smart factories and products: goods, components and production machines collect and share data in real-time and communicate with each other in order to self-manage production lines. This leads to a shift from centralized factory control systems to decentralized intelligence and allows high performance in terms of product design, production, and logistics systems (Trentesaux et al., 2016).

The Industry 4.0 represents the current trend of automation technologies in the manufacturing industry. The core enabling technologies of Industry 4.0 are Cyber-Physical Systems (CPSs), Internet of Things (IoT), big data and analytics, and cloud computing (Hermann et al., 2016; Zhong et al., 2016; Lu, 2017; Xu et al., 2018). Indeed, within the Industry 4.0, automation technologies, for instance robots, are connected via sensors to link the real and virtual world forming Cyber-Physical Systems. Through the Internet, CPSs cross-link all productive entities to each other. This communication of physical objects without any human interaction is known as the Internet of Things. Thanks to this interaction, a huge amount of data is generated (big data) and stored locally or in clouds. All these technologies together give rise to the smart factories characterizing the Fourth Industrial Revolution (Blunck & Werthmann, 2017).

In addition, Industry 4.0 includes also cutting-edge technologies such as additive manufacturing, simulation, augmented reality, artificial intelligence, autonomous robots, and horizontal and vertical system integration (Boston Consulting Group [BCG], 2015; Bahrin et al., 2016; Schwab, 2017; Rao & Prasad, 2018).

Each of these I4.0 enabling technologies is now explained in more detail with particular attention to its application in manufacturing.

2.3.1 Cyber-Physical Systems

The fusion of the physical and the virtual world is one important component of the Industry 4.0. This fusion is made possible by Cyber-Physical Systems (CPSs) which are “integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa” (Lee, 2008). As the word suggests, cyber-physical systems consist of physical and cyber components. A CPS is based on embedded systems[38], namely

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[38] An embedded system is a “computer system within some mechanical or electrical system meant to perform dedicated specific functions with real-time computing constraints” (Monostori et al., 2016). An example of embedded system is the anti-lock braking system (ABS) present in cars to regulate the brake force.

information processing computer systems that are embedded into a product and interact with the physical environment via sensors and actuators. However, unlike traditional embedded systems, such as smartphones, which are designed as stand-alone devices, in CPS various embedded devices are networked (Jazdi, 2014). Embedded systems are connected with each other through the Internet and share data with cloud computing. In this way data from many embedded systems can be collected and processed. Applications of CPSs include autonomous cars, robotic surgery, smart manufacturing, automated warehouses, intelligent buildings, and smart electric grid.

Within manufacturing, CPSs enable to connect machines and devices in production lines as a network. Sensors and actuators gather data that are stored and analysed in a cloud. As a consequence, real-time data are continuously available for decision-making, such as tasks' optimisation or reporting maintenance's needs (de Sousa Jabbour et al., 2018). In addition, CPSs react via actuator systems to processes within the physical world and therefore they can influence equipment's behaviour resulting in performance's improvement (Blunck & Werthmann, 2017). CPSs are the base for a self-organizing factory that entirely configures and organizes itself and responds to changing requirements, and where humans and machines seamlessly collaborate.

2.3.2 Internet of Things (IoT)

Internet of Things (IoT) is a things-connected network where "objects", such as RFID[39], sensors, actuators, machines, and mobile phones, communicate with one other, through unique identification codes, and cooperate to reach common goals (Giusto et al., 2010; Li et al., 2015).

Kevin Ashton, director of the Auto-ID Centre at MIT, firstly proposed the concept of IoT in 1999 referring the IoT as uniquely identifiable interoperable connected objects with radio-frequency identification (RFID) technology[40] (Ben-Daya et al., 2019). Connecting RFID readers to the Internet, they could automatically and uniquely identify and track in real-time

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[39] RFID is the key technology for making the objects uniquely identifiable. It is a transceiver microchip similar to an adhesive sticker. RFID system is composed of readers and associated RFID tags which emit the identification, location, or any other specifics about the object. The object related data signals are transmitted to the readers using radio frequencies which are then passed onto the processors to analyse the data (Farooq et al., 2015).

[40] Kevin Ashton had considered the possibility of using RFID tags to track products through firms' supply chains. RFID tags were used to read and identify objects and then transmit the information wirelessly through a network (Ben-Daya et al., 2019).

objects attached via tags. This created the IoT. Afterward, the IoT exploited other technologies, like sensors, actuators, GPSs, and mobile devices that are operated via Wi-Fi, Bluetooth or Near Field Communication (NFC) (Xu et al., 2018).

In IoT, as they are connected to Internet via sensors, things become “smart”. They have the ability to interact without human intervention, store and link related data, and offer access to it for a human or machine consumer. The “intelligence” of such devices can be revealed by cooperation in a network of other “smart” devices, which are able to check the system state updates and decide whether to act on them or not (Zuehlke, 2010).

Through the IoT it is possible to collect a huge amount of data that is analysed to generate added value for organizations. Indeed, real-time data gathered by sensors can be used, for example, to assess the usage and functionalities of products and to improve them, do better capacity planning, remotely monitor the status of physical objects, do predictive maintenance[41], as well as avoid stock-outs controlling inventory level, and help expedite timely decision-making (Lin et al., 2016).

2.3.3 Big data and analytics

Big data are the collection of massive amounts of data generated continuously by many different sources such as IoT devices, production equipment and systems, enterprise- and customer-management systems, and social media. What characterizes big data is that they arrive at an alarming velocity, volume, and variety[42] so that they require specific analytical technologies and methods to extract meaningful value from them. In fact, they represent dataset too large or complex to be dealt with by traditional database software. Therefore, big data ask companies to develop optimal processing power, analytics capabilities, as well as information management skills.

Big data analytics is used in manufacturing to monitor process, enhance flexibility, product quality, and energy efficiency, and improved equipment service through predictive maintenance (Kamble et al., 2018). Using big data enables to take better decisions since they are driven by data, namely by evidence rather than intuition. For this reason big data have the potential to revolutionize management (McAfee et al., 2012).

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[41] Predictive maintenance is a maintenance service based on predicting future machine’s failures. Equipment’s conditions are monitored through multiple sensors that collect real-time data about its components. In this way, component can be replaced before it fails, thus equipment downtime is minimized and the component lifetime is maximized.

[42] Data from different sources (sensors, texts, web, etc.) could be presented in completely different formats (tables, figures, natural languages, math equations, etc.).

2.3.4 Cloud computing

Cloud computing is the system that enables to create a virtual space where data are processed and stored. Through the Internet, the cloud computing allows access to applications and data saved on remote hardware instead of on the local workstation. Therefore, cloud computing implies a significant reduction in costs for companies since powerful hardware ─ expensive and subject to frequent maintenance ─ is no longer needed, but a machine capable of operating the cloud access application is sufficient[43]. In addition to the costs saving, the cloud system eliminates infrastructure complexity, extends work area, as it make possible data sharing across sites and company boundaries, facilitates operation, by ensuring that customers and employees simultaneously reach the same data, and provides access to information at any time (Oztemel & Gursev, 2020).

The cloud computing is strictly correlated with big data. Indeed, cloud systems are a good solution to handle and analyse the big data. Industrial data are highly sensitive, as they encapsulates information about products, business strategies, companies, and their customers and suppliers. The increasing connectivity has created vulnerability and has increased the risk of cyber-attacks (Kamble et al., 2018). Therefore, having a proper cybersecurity has become imperative for organizations to avoid malicious hacking into their systems, which leads to serious damage such as information theft, data destruction, quality defects in products, or production's sabotage.

2.3.5 Additive manufacturing

Additive manufacturing (AM) is the process of producing objects from a digital three-dimensional (3D) model by joining materials layer by layer, directly from raw material in powder, liquid, sheet, or filament form without the need for moulds, tools, or dies (Kellens et al., 2017). AM, also called 3D printing, is contrasted with the traditional subtractive or deformation-based manufacturing methodologies, which start from a block of material and shape it removing parts, through cutting or boring, or using dies to obtain the desired final geometry. As a result, additive manufacturing proposes a novel paradigm for engineering design and manufacturing.

AM provides large benefits to firms: it gives the possibility to realise unique and personalized products, thus increasing customer satisfaction, to produce complex part design, as it has very limited geometric constrains, and to manufacture small batch series at a relatively low average cost (Tuck et al., 2008; Abel et al., 2011). Moreover, it enables flexibility for design changes,

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[43] http://www.treccani.it/enciclopedia/cloud-computing/

reduction in time to market, as well as shorter process and assembly chains. However, AM presents also some limitations like a limited range of materials appropriate for use, low process productivity, long manufacturing time, and low surface quality (Kellens et al., 2017).

2.3.6 Simulation

Simulation is the process of leveraging real-time data to mirror the physical world in a virtual model, which can include machines, products, and humans. Thanks to computerised mathematical models of the real-world components, the simulation allows for the experimentation and validation of product, process, and system design and configuration. This technology can be used as a predictive tool for performances evaluation, or to compare alternative solutions before the real application in the production process, or to study and optimise machines' behaviour. For example, simulation makes possible for operators to test machine settings for the next product in line in the virtual world before the physical changeover, thereby driving down machine setup times and increasing quality (Mourtzis et al., 2014; Bahrin et al., 2016). The virtual simulated machine is said to be a "digital twin" of the physical machine. This one-to-one virtual replica of the technical asset contains models of its data (e.g. geometry or structure), functionality (e.g. data processing or behaviour) and communication interfaces. IoT, cloud, and big data analytics contribute to the creation of the "digital twin", which integrates all knowledge resulting from modeling activities in engineering and from working data captured during real-world operation (Schluse & Rossmann, 2018). The use of "digital twins" to simulate the behaviour of the actual machines enables the measurement of the performances of a production line without the need to actually put it into operation. This advantage exponentially reduces the times and costs necessary for the design of the line and for carrying out the tests. Furthermore, through the simulation it is possible to predict any system's critical issues and take actions in advance.

2.3.7 Augmented reality

Augmented reality (AR) is defined by Mourtzis et al. (2014) as "a real-time direct or indirect view of a physical real-world environment that has been enhanced or augmented by adding virtual computer-generated information to it".

AR systems aim at improving the way the user perceives and interacts with the real world. In the manufacturing environment, the application of augmented reality consists on an innovative and effective solution to assist and enhance the manufacturing processes. Indeed, AR provides workers with additional real-time information to improve decision making and work procedures. For example, humans can be guided through unfamiliar tasks or receive maintenance repair instructions visualizing information directly in the spatial context, through a viewer or tablet by simply framing real objects involved in the process (Kamble et al., 2018). Furthermore, AR can help operators to identify faulty or defective components, or, for instance in logistics, it can be a means of locating spare parts in a warehouse or verifying order compliance in real-time.

It is important to underline that augmented reality does not coincide with virtual reality, another term used in the I4.0 context. While the former integrates virtual data with the real environment, the latter creates simulated experience that can be similar to or completely different from the real world.

2.3.8 Artificial intelligence

Artificial intelligence is a collection of different technologies ─ from machine learning to natural language processing ─ that are brought together to enable machines to act with what appears to be human-like levels of intelligence. AI allows a machine to sense, comprehend, act, and learn[44]. Traditional computers can't fix problems on their own. On the contrary, with machine learning, they can learn from past data and results, and make better decisions in the future[45]. In addition, computers are programmed to identify written and spoken words, but to really communicate with people, they need to understand context. New generation computers use natural language processing to look beyond individual words or phrases, and understand the context they're being delivered in. Natural language processing lets virtual assistants like Siri by Apple or Alexa by Amazon[46].

Artificial intelligence is useful for big data analytics as it can extract valuable information from the raw data and generate insightful advices and forecasts enhancing decision making (Kibria et al., 2018).

AI technology applied in manufacturing can bring important benefits to companies. For example, predictive maintenance uses advanced AI algorithms to formulate predictions

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[44] Through AI a machine perceives the world around it by acquiring and processing data, understands the information it collects by recognising patterns, takes actions in the physical or digital world based on that comprehension, and, finally, continuously optimises its performances by learning from the success or failure of those actions.

[45] The learning ability of AI is a fundamental element. Being able to decide through an analysis of data which actions are necessary to complete an activity, rather than being coded to act in a predefined way, is what makes a system "intelligent", and which differentiates AI from other forms of automation.

[46] https://www.accenture.com/it-it/insights/artificial-intelligence/what-ai-exactly

regarding asset malfunction. This allows for drastic reductions in costly unplanned downtime, as well as for extending the remaining useful life of production equipment. Moreover, AI algorithms can notify of emerging production faults, such as deviations from recipes or subtle abnormalities in machine behaviour, that are likely to cause product quality issues or reduce productivity.

2.3.9 Autonomous robots

Autonomous robots are intelligent machines capable of performing tasks in the world by themselves, without explicit human control[47]. They offer accuracy, speed, durability, and flexibility and are able to cooperate with one another and with workers. In manufacturing they automate repetitive tasks, reduce margins of error to negligible rates, and enable human workers to focus on more productive areas of the operation.

Autonomous robots are widely used in production and logistics to increase efficiency and productivity. Some examples are dual-arm robots that distributes material in assembly lines or automated guided vehicles able to handle goods inside the factory. They interact with other machines and with humans by autonomously reconfiguring their trajectory according to process needs or adapting to the flow of workers within the production areas (Mueller et al., 2017).

2.3.10 Horizontal and vertical system integration

Horizontal and vertical integration in Industry 4.0 refers to the adoption of specific information systems capable to interact and exchange information with suppliers and customers (vertical integration) or across the entire organization, from inbound logistics, through warehousing, production, marketing and sales, to outbound logistics (horizontal integration).

A company can obtain several benefits from these integrations achieved by digital technologies. Be interconnected to upstream suppliers, for instance through the IoT technology, allows companies to react rapidly to changes in the production, adjusting quickly the stock levels as suppliers have all the information to provide materials and components on time. At the same time, the integrations with downstream distributors enables to better understand demand trends and adapt the production accordingly. In addition, the direct connection with customers permits to collect information about them and how they use

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[47] https://mitpress.mit.edu/books/autonomous-robots

products, thus giving the possibility to provide more personalized goods and services (Gilchrist, 2016).

Furthermore, the integration of the whole value chain can lead to important advantages since it allows to optimise the coordination between different firm's activities.

2.4 How I4.0 technologies can support companies in implementing CE principles

A massive volume of researches has been carried out on the concepts of Industry 4.0 and Circular Economy; separate queries in Scopus using "Industry 4.0" and "Circular Economy" as keywords yield 4,060 and 13,911 published documents, respectively[48]. Nevertheless, the nexus of these topics has been little investigated; a combined search using both "Industry 4.0" and "Circular Economy" as keywords shows only 89 papers, of which 67 published between 2019 and 2020[49]. Moreover, most of these existing works deals with the interaction between I4.0 and CE, but the way in which digital technologies can favour the transition toward CE has been rarely assessed (Rocca et al., 2020).

Within the following the potential of Industry 4.0 applications will be analysed with regard to the circular economy; in particular, it will be evaluated how Industry 4.0 elements are able to ease the implementation of CE principles.

As described in chapter one, circular economy is based on 3 fundamental principles ─ Reduce, Reuse, and Recycle ─ to which three other principles, introduced by the Ellen MacArthur Foundation, are added, namely "Design out waste and pollution", "Keep products and materials in use" and "Regenerate natural systems". However, the two principles of the Foundation "Design out waste and pollution" and "Keep products and materials in use" can be seen as specific actions to fulfil the more general principles of Reduce and Reuse/Recycle respectively. In fact, intervening in the design phase, so as to design products that ensure waste is not created in first place, is an excellent way to follow the Reduce principle. On the other side, keep products and materials in use by developing products so they can be repaired, remanufactured, or recycled is a means to meet the general principles of Reuse and Recycle. For this reason, in dealing with the potential impact of I4.0 technologies on the CE, Reduce and "Design out waste and pollution" will be kept together, and the same will be done for Reuse and "Keep products and materials in use". Although, as mentioned above, the latter is also linked to the Recycle principle, it will be discussed together with Reuse as in this section,

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[48] The research has been done on 6 July 2020.

[49] This underlines that these topics are gaining more and more relevance in the actual scenario.

when mentioning “Keep products and materials in use”, the focus will be on keeping in use through reusing products and materials, not recycling them.

Recycle principle will be addressed individually as well as for the third principle expressed by the Ellen MacArthur Foundation, “Regenerate natural systems”.

In the next paragraphs, it will be discussed how and which Industry 4.0 technologies can help companies in the fulfilment of each of these CE principles.

2.4.1 Reduce & Design out waste and pollution

The circular economy removes the negative impacts of economic activity that cause damage to human health and natural systems[50]. It is aimed at reducing waste generation and minimising the input of materials and energy, thus increasing production efficiency.

An overview of the literature concerning the relationship between CE and Industry 4.0 shows that there are a lot of I4.0 technologies which can help to meet Reduce and “Design out waste and pollution” principles. These technologies are cyber-physical systems (CPSs), IoT, big data and analytics, cloud computing, additive manufacturing, simulation, augmented reality, artificial intelligence, autonomous robots, and horizontal and vertical system integration. Now it will be described how each of these elements can act as an enabler of the two CE principles.

Cyber-Physical Systems

Cyber-Physical Systems (CPSs) are the key objects linking together all I4.0 technologies. They are ICTs systems that connect machine tools and devices as a network, thus monitoring and exchanging real-time data for decision making. CPSs represent a paradigm shift in manufacturing process that can hasten the transition to a circular economy. They enable resource-efficient production processes by gathering data from processes and objects, such as machines within the factory. Therefore, efficiency of machines could also be assessed in real-time in order to plan maintenance, thus avoiding excessive use of resources, and to identify failures, which might create waste. In addition, based on the parameters of production and consumption of resources ─ for example, energy ─ managers could monitor and control the performance of operations optimising resource usage (de Sousa Jabbour et al., 2018).

Moreover, artificial intelligence can be combined with CPS to add intelligent decision-making capability. The integration of this technology in energy systems not only can change their design principle and operation regime, but also bring important benefits such as energy efficiency enhancement (Inderwildi et al., 2020).

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[50] https://www.ellenmacarthurfoundation.org/

IoT

The IoT is considered, together with AM, one of the most important technologies able to support the transition to the CE (Rosa et al., 2020). Thanks to the IoT it is possible to observe processes in real-time. The interconnection of machines, products, and humans make everything traceable and transparent, included consumption of resources. Therefore firms are able to exactly assess the amount of resources needed for each production step; processes with excess resource consumption can be identified and so optimised or eliminated.

IoT also makes it possible to trace energy and water consumption during all production phases as well as the time each step requires. The optimisation of the production time does not only save time, but shorter production processes typically consume less resources like energy.

Furthermore, IoT eases inventories' management. Through real-time data about stock levels it is possible to reduce inventory[51]. Indeed, too much stock leads not only to great capital costs, but also to unused and excess resources. Reductions of inventory levels decreases energy needs for the proper storage of goods as well as waste created by materials turning old or outdated (Blunck & Werthmann, 2017).

Big data and analytics

Big data and analytics are key enablers for implementing CE as the collection and analysis of a huge amount of data generated within a factory gives the possibility to better identify issues related to material and energy flows and structural waste. Big data analytics can improve resource efficiency identifying periods when production is less intensive in its use of resources. These moments indicates times of the day or of the week when a product can be manufactured with, for example, half of the energy or CO_2 emissions for same product manufactured at a different moment. Similarly, big data analytics can be helpful to anonymously compare performances between firms to identify resource consumption patterns and establish if opportunities for more resource-efficient production exist (Demartini et al., 2019).

Moreover, data analytics allows more accurate demand forecasts that leads to reductions in waste as needed input materials can be projected more precisely and overproduction can be eliminated (Blunck & Werthmann, 2017).

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[51] For instance, real-time data about inventory levels enable an intelligent system to automatically reorders if the minimum fill level is reached, avoiding surplus materials (Blunck & Werthmann, 2017).

Cloud computing

Internet of Things, big data and analytics, and cloud computing are technological innovations that have the power to accelerate the circular economy (Kallio et al., 2018). Embedded sensors, processors, and software in products are coupled with a cloud in which product data are stored and analysed. As described in previous paragraphs, these data can be used to improve product functionality and performance, the efficiency in resources usage, and to reduce waste.

Moreover, cloud computing is a key to lower energy consumption and therefore CO_2 emissions. Since cloud technologies are optimised to serve thousands of customers at the same time, they make it possible to save up to 50% energy, as well as allow a greater degree of server utilization. In addition, cloud data centers are designed to reduce energy waste by exploiting optimised technologies for cooling and powering systems[52].

Additive Manufacturing

Additive manufacturing (AM) has been identified as having the potential to provide a number of sustainability advantages. First of all, AM allows to fully reach the CE principle of reducing waste as, being an additive process, it enables to use the exact amount of material needed for the goods' production without material wasting. Secondary, AM improves resource efficiency thanks to its capacity to optimise geometries. It creates lightweight components, and goods comprising of fewer parts decreasing material consumption in manufacturing and energy consumption in use, with the subsequent reduction in transportation. Moreover, AM gives the possibility to move directly from the design to the production phase by eliminating the intermediate steps of making tools and moulds thus further reducing the use of materials and making the production of small batches convenient. Furthermore, it enables to reduce or eliminate inventory waste, including unsold and obsolete parts, due to the ability to create small-scale production and spare parts on-demand. Finally, AM reconfigures value chains which become shorter, simpler, more localised and collaborative offering significant sustainability benefits. AM, indeed, gives the possibility to keep production and consumption close, by producing exactly where you want to consume, with a very strong impact on logistics and reducing the environmental impacts associated with transportation (Ford & Despeisse, 2016).

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[52] http://juniortek.net/blog/cloud-computing-ambiente/

Simulation

Simulation can improve the efficiency in exploiting natural resources. In fact, simulation techniques can be leveraged for calculating a set of eco-efficiency indexes like raw material suitability and utilization (%)[53] and resource utilization efficiency (%)[54], that cover the mass balances of raw material to products, or like residue utilization and repurposing (%)[55], which deals with material efficiency from the waste minimization perspective.

The use of simulation tools in environmental analysis opens up new possibilities: the analysis is no longer locked to predefined process data, but can be used as a tool for industries to find the most environmentally sustainable production methods and the chief culprits that are making the production and system unsustainable. Process simulation tools help in interpolating data when they are missing, decreasing uncertainties with allocation issues, capturing unknown compounds, and finding limits for specific technologies and inputs (Rönnlund et al., 2016).

Furthermore, with the use of simulation, manufacturers can test products without creating physical prototypes, which means less waste and resource consumption in the testing phase.

Augmented reality

Augmented reality (AR) is a valuable technology to drive for resource efficiency as it enables companies to see energy, water, and waste flows in real-time in the factory setting. Firms can use AR to apply the traditional skills of productivity improvement enhanced with deep layers of data to define exact areas for operational improvement (Demartini et al., 2019).

AR reduces the resources used in design and prototype phases because it allows to convert projects' files into 3D virtual 360-degree experiences and therefore saving resources required for seeing the prototype in the real-world. Moreover, AR can support waste management. Manufacturers build their reputation on the quality and consistency of their products and for this reason they strive for production outputs to meet certain standards. However, errors in

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[53] The indicator raw material suitability and utilization (%) describes how effective the recovery process is; it measures the recovery rate of products from total raw material inputs. In material efficient production concepts, nearly all fractions are utilized for sellable products, indicating efficient utilization of production side streams.

[54] For instance, in the metallurgical industry, the indicator main metal utilization efficiency (%) describes the efficiency of the technology to produce products from the metals in the raw material. The indicator describes the percentage of main metals that ends up in products.

[55] Residue utilization and repurposing (%) looks at the balance between repurposed material and residues. Residues can be used in the same or another process. The value is compared against percentage thresholds defined by achievements of similar products.

production processes, such as wrong assembly or incorrect raw materials quality assessment, can occur when workers don't adhere closely to standards set by the company, resulting in defective products and ultimately in waste. AR can give an important contribution in preventing waste as it can avoid errors by providing work instructions into one visual experience that people can view while physically working[56].

In addition, this technology allows people to work in a completely immersive digital environment either individually or collaboratively. As a consequence, it is suitable for remote working reducing GHG emissions by eliminating the need for travel.

Artificial intelligence

Artificial intelligence (AI) can play an important role in designing out waste and pollution. AI can enhance and accelerate the development of new products, components, and materials fit for a circular economy through iterative machine-learning-assisted design processes that allow for rapid prototyping and testing. Businesses can harness AI by using it to choose more efficiently the materials used in products, analyse the properties of materials, and improving manufacturing techniques (EMF, 2019a).

Furthermore, AI notifies the presence of non-compliance with quality standards along the production process and it can interrupt it before further waste is generated. Moreover, AI can largely contributes to energy saving. For instance, in data centers it can be applied to optimise the energy efficiency of the cooling systems, resulting in a great reduction in energy usage.

Autonomous robots

Increasingly, autonomous robots are programmed with artificial intelligence to recognize and learn from their surroundings and make decisions independently. This technology can help in increasing efficiency in resource utilization and enhancing productivity. The application of autonomous robots in manufacturing makes it possible to greatly reduce error rate and the need for re-work thus resulting in a large reduction in waste[57].

Horizontal and vertical system integration

When production systems become even more digital, intelligent, and connected, value chains become increasingly integrated and transparent. In general, thanks to Industry 4.0

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[56] https://www.ptc.com/en/thingworx-blog/3-forms-of-waste-oems-can-reduce-with-augmented-reality

[57] https://www2.deloitte.com/us/en/pages/manufacturing/articles/autonomous-robots-supply-chain-innovation.html

technologies, like RFID, everything become traceable into the supply chain. This, for example, enables companies to efficiently track and manage inventories, consequently reducing unnecessary transportation requirements and fuel usage (Blunck & Werthmann, 2017).

Moreover, RFID and IoT technologies allow connection with suppliers bringing important benefits in terms of reducing the inventory of raw materials and the potential for waste. For instance, a company that has a just in time logistics that is tracked can eliminate waste as it receives raw materials exactly when it needs it for the production and in just the amount required for that specific production.

Sharing information across the entire organization via digital technologies like IoT allows firms to better coordinate their activities, and at the same time contributes to the fulfilment of CE principles. For example, a company that relies on multiple production facilities and is able to integrate data about all of them ─ inventory levels, unexpected delays, number of products manufactured, and so on ─ can avoid wasteful inventory duplications or redundant production activities.

2.4.2 Reuse & Keep products and materials in use

A circular economy approach encourages to keep product and material in use. In order to do this designers and manufacturers have to extend the usage period of products through activities such as design for durability, reuse, remanufacture, repair, or refurbishment (EMF, 2019a). Reuse principle refers to the reuse of the product as a whole, or its components, after its first life-cycle, for subsequent life-cycles, to reduce the consumption of virgin materials required to produce new products and components (Jawahir & Bradley, 2016).

Many technologies have been identified in literature to fulfil the Reuse and "Keep products and materials in use" principles. They are cyber-physical systems (CPSs), IoT, big data and analytics, cloud computing, additive manufacturing, simulation, augmented reality, artificial intelligence, autonomous robots, and horizontal and vertical system integration.

Cyber-Physical Systems

CPSs enable either a better lifecycle management of products and services ─ for maintenance reasons ─ or an enhanced remanufacturing practice (Rocca et al., 2020).

CPSs throughout a factory can be created through retrofitting. Indeed, retrofitting assets is an easy way of upgrading existing manufacturing equipment with sensor and actuator systems as well as with the related control logics. This is a cost-efficient way to make assets "intelligent" and to know their location, condition, and availability (Blunck & Werthmann, 2017). The collection of data to monitor an asset's condition enables users to define thresholds to initiate actions or notifications that allow condition based reactions. This makes predictive maintenance possible, which in turn allows to replace failing components prior to their failure, thus extending usage life and minimizing downtimes.

IoT

Potentially, IoT usage extends a product/component life cycle. For example, IoT and intelligent assets, which can sense, communicate, and store information about themselves, can also signal any problem, determine when the need for repair arises, and schedule their own maintenance[58].

Through the incorporation of "smart materials", equipped with sensor- and actuator-technology, these resources can be observed not only during the production process itself, but also throughout the whole life cycle of the product they are incorporated in. Monitoring the state and location of valuable materials ─ for instance rare metals used in electronic parts ─ by using RFID-technology reduces waste and increases the reuse of these scarce resources. This enables, or at least eases, to hold technical and biological nutrients within their cycles (Blunck & Werthmann, 2017).

Big data and analytics

Real-time data regarding the condition of equipment are used to anticipate maintenance and repair needs, and to flag a necessity of remanufacturing or replacement of components prior to their failure, therefore allowing to repair parts instead of substitute them with new ones. This allows a better management of assets, extending their usage cycles and maximize their utilization (World Economic Forum, 2017).

Cloud computing

IoT and cloud computing create visibility and intelligence into assets. This intelligence can be knowledge of the location, condition, or availability of the tools (Kallio et al., 2018). As explained before, these I4.0 technologies support a more circular economy, for instance, by making products easier to maintain and repair. Indeed, by adding intelligence to a product or device, it becomes possible to create an asset that can signal problems, determine when it needs to be repaired, and schedule its own maintenance.

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[58] https://citiesofthefuture.eu/how-the-internet-of-things-enables-the-circular-economy/

Additive manufacturing

AM contributes to Reuse and "Keep products and materials in use" principles as it extends product life. There are two distinct technical approaches through which AM is being used to do this (Ford et al., 2015). The first one is product redesign leading to improvements in durability. The greater freedom in shape and geometry offered by this category of manufacturing processes allows to design more durable products and components. Product improvements generate benefits during the product use phase and at the product's end-of-life, such as increased strength and stiffness, corrosion resistance, and improved operational efficiency, functionality, and ease of manufacturing and maintenance. The second approach through which AM extends product life is the production of make-to-order spare parts that can be manufactured also in-situ. As a consequence, repair and remanufacturing processes, that enhance the product utilization, are made easier and cheaper. Producing one-off spare parts on demand in order to repair a machine is prohibitively expensive using traditional manufacturing technologies, however the economics of AM make it ideal for make-to-order spare parts thus eliminating or at least minimising inventory waste. This supports repair since it reduces inventories and eliminates storage room, making repair more affordable (Sauerwein et al., 2019). In addition, the availability of digital designs enables in-situ repair and remanufacturing avoiding the environmental impact related to spare parts' transportation. This can lead to a change in business model because it could no longer be the physical product to be sold, but its virtual model, which could be printed directly by the user. Furthermore, 3D printing also reduces waste material generation during the repair process, as each spare part is produced using the exactly amount of material required, without waste (Ford & Despeisse, 2016).

Simulation

Within the I4.0 paradigm, simulation is used to replicate real world behaviours in virtual environments; this way, physical and virtual dimensions coexist and are synchronized thanks to the creation of a "digital twin", a virtual representation of physical object, coping its behaviour through a real-time data acquisition from the field. From a CE perspective, simulation is related to either the virtual optimisation of disassembly process within End-of-Life phase ─ simulation is used as a tool for monitoring what happens in the system during the disassembly process, trying to optimise energy consumption and valuable materials recovery ─ or support in remanufacturing of complex products ─ for example in the form of decision-support tools. Indeed, the digital twin allows for the real-time interaction with the products in order to store knowledge about components and materials embedded into them. Data extracted can be used for a better decision-making process (Rocca et al., 2020). For instance Xi Vincent Wang and Lihui Wang (2019) focused their analysis on the waste electrical and electronic equipment (WEEE) recovery. The WEEE digital twin is initiated based on the cyber knowledge from the product design phase; the components, material, and most importantly hazardous substances are integrated and maintained in the product documentation. When the product is sold to an end user, data about the product status, upgrades, repairs, and maintenance are updated via various I4.0 enablers, such as mobile apps, smart tags, and so forth, and maintained inside the mirrored digital twin. When the device reaches its end of life, it is transported to the remanufacturer that can initiate the operation of recovery at the component or material level or discard, without the need of additional test or evaluation, as all necessary data are already stored in the digital twin. All the recovery and reconditioning information is recorded and stored as part of the new product's digital twin. Hence, it forms a continuous and sustainable data flow; the full knowledge of the product, components, and materials is well maintained in the digital twin for the future product analysis and decision-making.

In addition, simulation can play a large role in the CE by enabling manufacturers to design for longevity. Different materials can be simulated to assess the product life cycle and how a material may be re-used once a certain product has reached the end of its cycle[59].

Augmented reality

AR supports repair allowing work to be completed by non-experts, as long as they're able to follow instructions, either preset based on a diagnosis, or provided by a colleague in a remote location. Moreover, AR can ease repair process by identifying faulty components and repairing them before they break, thereby extending objects life cycle.

Artificial intelligence

AI can help to build and improve the reverse logistics[60] infrastructure required to "close the loop" on products and materials by improving the processes to sort and disassemble products, remanufacture components, and recycle materials (EMF, 2019a).

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[59] https://blogs.3ds.com/simulia/harnessing-power-simulation-circular-economy/

[60] Rogers and Tibben-Lembke (1999) defined reverse logistics as "the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

Autonomous robots

Autonomous robots can be used in order to efficiently disassembly products enabling the maximization of resource utilization via re-usage, and consequently a minimization of pollution. Disassembly process has become more and more complex due to the wide variety of goods as well as their shape at the time of their disposal. However, developments in robotics have made machines more autonomous and flexible thus becoming suitable for supporting CE practices of disassembly and remanufacturing (Rocca et al., 2020).

Horizontal and vertical system integration

Information systems capable to interact and exchange information with customers can have an important influence on CE practices. In a circular approach, customer relationships cannot end at the point of sale. Connection with clients must be kept in order to collect information about product usage and conditions; this makes it possible to extend the product lifecycle management beyond the producers' boundaries. Connected devices are likely to slash the customer cost of a repair as the issue can be diagnosed by the organisation, avoiding call-out fees and costly mistakes. So this could encourage customers to repair, rather than replace, their belongings (EMF, 2018).

When the product comes to its end-of-life or is no longer used, the connection with customers allows companies to invite them to return items, therefore getting as much material back as possible. Then companies can give a second life to products, remanufactured them or recycle their materials.

2.4.3 Recycle

Within a circular economy, when reuse, remanufacture, repair, or refurbishment are no longer feasible, efforts to recover the value of materials come into play (EMF, 2019a). One possible way is through recycle. Recycle involves the process of converting materials, that would otherwise be considered waste, into new materials or products (Jawahir & Bradley, 2016).

The implementation of Recycle principle can be supported by I4.0 technologies like cyber-physical systems, cloud computing, IoT, big data and analytics, additive manufacturing, autonomous robots, artificial intelligence, and horizontal and vertical system integration.

Cyber-Physical Systems & Cloud computing

CPSs, together with the IoT and cloud computing, can provide detailed information about products at the end of their useful life. Chips and sensors provide users data either about components and materials embedded into products, or about disassembly and recycling procedures; as a consequence, it is possible to obtain a more efficient materials reintroduction into new product value chains (Rocca et al., 2020).

IoT

By collecting and analysing product-related data through IoT, products can be disassembled and recycled more easily. In addition, IoT also provides process-related data by optimising remanufacturing and recycling practices (Rocca et al., 2020).

Big data and analytics

Some scholars have considered the possibility to exploit big data and analytics to develop automated approaches assessing potential value pathways for secondary materials or discovering potential industrial symbioses, so that waste or by-products from industrial productions are reused or recycled becoming raw materials for another firm (Davis et al., 2017; Song et al., 2017).

Lin (2018) focused on the exploitation of big data analytics for considering recycling issues during the product design. Design for recycling is an eco-design strategy; eco-design is a systematic approach allowing the design of more environmentally friendly products.

Additive manufacturing

A great feature of the materials that are used in 3D printing is their ability to be melted down and re-extruded without a significant loss of material. This generates an important benefit in term of recycle. Indeed, almost all material ─ powder or resin ─ that compose a 3D printing's object are reusable. For metal powders it is estimated that 95-98% can be recycled. In addition, AM enables simplified assemblies with less material diversity that improves opportunities for recycling. Recently new 3D printers have been designed to work with filaments made partially of recycled plastic.

Autonomous robots & Artificial intelligence

Autonomous robots enable to facilitate and make more efficient recycling procedure. Companies combine AI and robotics to recover recyclables from waste. Post-consumer mixed material is monitored by cameras and sensors, then AI examines carefully real-time data collected by sensors and provides an accurate analysis. Based on this analysis, robots make autonomous decisions on which objects to pick, separating the waste fractions quickly with high precision. This technology allows great flexibility in waste sorting and rises the rate of recovery and purity of secondary materials, thus improving performance and efficiency of recycling process. The result is an increase in the value generated from material streams (EMF, 2019a).

Horizontal and vertical system integration

As said for the principles Reuse and “Keep products and materials in use”, to exchange information with customers allows companies to manage product life also in the post-sale. This can strongly favour recycling practice. Firms can identify when products come to their end-of-life and exploit this information to incentivise customers, for instance giving a voucher for a new purchase, to give back the product, whose materials can be recycled.

2.4.4 Regenerate natural systems

The third principle expressed by the Ellen MacArthur Foundation, “Regenerate natural systems”, refers to the use of renewable energy, such as solar, wind, or biomass, and materials, which are made of natural resources that can be replenished, generation after generation, like wood or fabrics made of vegetable or animal origin.

From the literature analysis, big data and analytics, IoT, additive manufacturing, and artificial intelligence have emerged as the key enabling I4.0 technologies to reach this CE principle.

Big data and analytics & IoT

Big data have a great positive impact also in renewable resources field. They have the potential to change the future of the renewable energy sector; big data enable the optimisation of the energy production and its distribution. Intermittent and unpredictable resources ─ like wind and sunlight ─ often hamper the renewable energy production. As a result, it becomes difficult for solar and wind power plants to operate at their maximum potential. However, big data are rapidly changing this scenario. Thanks to the advancements in big data, predictive analytics, and machine learning, data collected by power plants can now be combined with weather and satellite data. Thus, technology can predict weather conditions well in advance, allowing renewable plants to increase their production significantly. Instead of increasing the number of solar panels or wind turbines, the idea is to increase the efficiency of existing plant infrastructure[61].

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[61] https://www.smartdatacollective.com/big-data-changing-future-renewable-energy-sector/

In addition, with the help of IoT and big data and analytics, companies can largely improve their operations and management which has become increasingly difficult, affecting the daily energy output of the plant[62]. Indeed, a massive solar power plant, for example, consists of hundreds or thousands of solar panels, different types of sensitive equipment, sensors, installers, inverters, and a complex web of wires. The large benefits provided by big data increasingly encourage the adoption of renewable energy sources.

Additive manufacturing

AM can be exploited for regenerating natural systems through the use of materials based on renewable sources. Recently, a number of studies were published on sustainable alternatives for 3D printing materials. Tenhunen et al. (2018) printed cellulose-based materials on cellulosic fabrics; Mogas-Soldevila and Oxman (2015) developed 3D printable materials based on chitosan and water, being fully recyclable upon contact with water; and Faludi et al. (2019) calculated the sustainable gain of a pecan shell-based 3D printing material in comparison with ABS (Acrylonitrile Butadiene Styrene). These materials are based on abundant and local resources and, therefore, they also satisfy the need to close the system on a local scale (Sauerwein et al., 2019).

Artificial intelligence

AI technology can be a helpful tool to enable designers to substitute harmful chemicals and materials. To design a new material, scientists need to evaluate a significant amount of data about the structure and the properties of materials which requires time. On the contrary, AI can analyse data quickly and therefore can suggest new materials and predict the toxicity of chemicals in a more efficient way (EMF, 2019a).

2.5 Conclusions

By examining the available literature, it emerges that various I4.0 technologies can act as enablers of the Circular Economy. Starting from the results arisen from the literature analysis, in Table 2 it is proposed a summary of the role of the I4.0 technologies in implementing the

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[62] A management program based on big data collects sunlight intensity data accurately eliminating the need for expensive on-site sensors. The analytics tool enables to verify how well solar panels perform under varying weather conditions compared to their ratings. The software can send a signal whenever solar panels underperform or overperform, thus locating the problem quickly and taking the appropriate action. As a result, operations and maintenance costs are reduced considerably.

circular model, highlighting the degree of contribution from each I4.0 technology to the CE principles. The dots represent the level of intensity with which the technology can support companies in implementing the CE principles. Three dots indicate that the technology gives a large contribution in meeting the CE principle; two dots stand for a lower contribution, and one dot means that the technology offers little support in the fulfilment of the CE principle. Where there are no dots, this suggests that the technology does not represent an enabler for the CE principle.

Table 2 – The role of I4.0 technologies in implementing CE principles

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	○○○	○○	○	
Internet of Things (IoT)	○○○	○○○	○	○
Big data and analytics	○○○	○○○	○○	○○
Cloud computing	○○	○	○	
Additive manufacturing (AM)	○○○	○○	○○○	○○
Simulation	○○○	○○○		
Augmented reality (AR)	○○○	○○		
Artificial intelligence (AI)	○○○	○○	○○	○○
Autonomous robots	○○○	○○	○○	
Horizontal and vertical system integration	○○	○○	○○	

Source: own elaboration

From the Table 2 it is possible to notice that all the I4.0 technologies contribute, almost always very significantly, in meeting CE principles of Reduce and “Design out waste and pollution”, and Reuse and “Keep products and materials in use”. For what concerns Recycle and “Regenerate natural systems” principles, instead, fewer technologies are useful for the CE aims and they often provide a lower contribution than they do for the other principles.

In addition, CPSs, IoT, big data and analytics, cloud computing, and additive manufacturing, together with artificial intelligence, autonomous robots, and horizontal and vertical system integration, all result as the I4.0 technologies able to support a greater number of principles. In particular, IoT, big data and analytics, additive manufacturing, and artificial intelligence contribute to all CE principles.

CHAPTER 3
SMART GREEN FACTORY

3.1 Introduction

In the current scenario the concept of Industry 4.0 is omnipresent; it is strongly connected to megatrends like digitization and connectivity. Within the smart factory of the Industry 4.0, production is connected to the latest communication and information technology (Blunck & Werthmann, 2017). As seen in the previous chapter, technologies enabling the Industry 4.0 have the potential to support the implementation of the circular economy principles.

In this chapter, the concepts of smart factory and green factory will be examined in depth, describing their characteristics and functioning. Later, the two themes will be brought together analysing the smart green factory, a company that simultaneously adopts CE and Industry 4.0 approaches. Moreover, it will be explained a roadmap for firms that want to realise a more sustainable manufacturing by using I4.0 technologies.

3.2 Smart Factory

Nowadays people are surrounded by many things that are called "smart". With regard to objects, the adjective smart indicates an independent device that is enhanced by implementation of additional features, which introduce multi-platform communications and increase its computational abilities. A smart device usually consists of a sensor, and/or an actuator, a microcomputer, and a transceiver. Smart objects have the ability to store and link related data, to give humans or machines access to them, to check their state updates, and decide whether to act or not, as well as the ability to cooperate in a network of other smart devices (Zuehlke, 2010).

Scholars have started to use the adjective smart also referring to manufacturing facility, giving life to the term "smart factory". The intelligent enterprise, or smart factory, is the result of the integrated application of all the enabling technologies of Industry 4.0 to the traditional enterprise. Thanks to CPSs, IoT, big data and analytics, and artificial intelligence the firm becomes "smart", so it is able to take optimisation decisions that typically humans make. Various practitioners and scholars have dealt with the smart factory concept, but there is no consensus about a clear definition of the term (Radziwon et al., 2014). Yoon et al. (2012) defined it as "a factory system in which autonomous and sustainable production takes place by gathering, exchanging and using information transparently anywhere anytime with networked interaction between man, machine, materials and systems, based on ubiquitous technology and manufacturing technology". According to the vision of Zuehlke (2010), smart factory is a way towards a factory-of-things, where IoT is perceived as an open network of items equipped with enough computing and communication capabilities to give them the ability to act independently, without direct human intervention. Furthermore, the economic development agency Germany Trade and Invest described the smart factory as "a flexible system that can self-optimise performance across a broader network, self-adapt to and learn from new conditions in real or near-real time, and autonomously run entire production processes"[63].

The smart factory represents a leap forward from more traditional automation to a fully connected and flexible system. It uses a constant stream of data from connected operations and production systems to learn and adapt to new demands, to drive manufacturing, maintenance, inventory tracking, and digitization of operations across the entire manufacturing network ─ for instance through the creation of digital twins. However, it is important to note that the smart factory is not the "end state"; given the rapid pace of technological development, it rather represents an ongoing evolution toward building and maintaining a flexible learning system (Deloitte, 2017).

Manufacturers have more and more embraced automation, nevertheless in many factories each automated processes is disconnected with one another, requiring frequent human intervention to handle transitions between various phases of operations. On the contrary, the smart factory eliminates barriers between phases to automate data analysis and operational workflows more deeply in a single connected ecosystem.

3.2.1 Key characteristics of a smart factory

Connectivity, optimisation, transparency, proactivity, and agility are some of the major features of the smart factory.

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[63] https://industrie4.0.gtai.de/INDUSTRIE40/Navigation/EN/Topics/Industrie-40/smart-factory.html

Connection is the most important characteristic of the smart factory. In an “intelligent” factory, IoT allows devices to communicate and interact between them and with centralized controllers. Assets are fitted with smart sensors so that data about the entire production process can be collected and constantly updated. Real-time data enable collaboration across departments ─ such as feedback from production to product development ─ and make the smart factory more responsive, proactive, and predictive. In addition, an overall supply network efficiency becomes possible thanks to the integration of data from operations, business systems, suppliers, and customers.

In a smart factory, optimisation is made possible as operations can be executed with minimal manual intervention, but with high reliability. Automated workflows, synchronization of assets, improved tracking and scheduling, and optimised energy consumption inherent in the smart factory can increase asset uptime and production efficiency, and minimized cost and waste.

In the smart factory, a high level of transparency is reached. Thanks to the continuous data collection, the history of any component or product is logged and can be accessed at any time, ensuring constant traceability. This creates great visibility across the facility and provides company live metrics and tools ─ like real-time alerts, notifications, tracking, and monitoring ─ to support quick and consistent decision making.

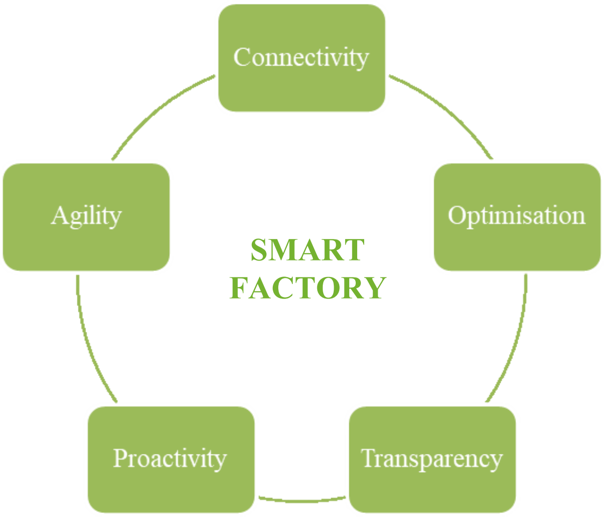
Proactivity is the fourth feature characterizing the smart factory. In a proactive system, instead of reacting to issues and challenges after they occur, companies anticipate and act before they arise. Within a factory, this can include identifying anomalies, restocking and replenishing inventory, predictively addressing quality issues, and monitoring safety and maintenance concerns. A smart factory has the ability to predict future outcomes based on historical and real-time data. For instance, enacting a digital twin, manufacturers can digitize an operation and move beyond automation and integration into predictive capabilities.

Finally, a smart factory is agile. It can self-configure the equipment and material flows depending on the product being built and schedule changes, and then see the impact of those changes in real-time. As a consequence, a smart factory is able to easily adapt to schedule and product variations (Deloitte, 2017).

Each of these features can play a role in enabling more informed decisions and help organizations improve production processes.

The figure 8 illustrates the main features of a smart factory.

Figure 8 – Major features of a smart factory

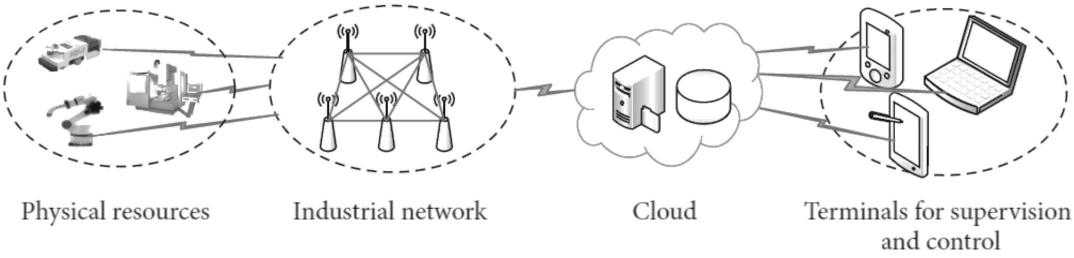


Source: own elaboration

3.2.2 Smart factory architecture

Within a factory, various physical or informational subsystems are involved during production and management activities. These subsystems are present at different hierarchical levels, for example, the actuator and sensor, control, production management, manufacturing and execution, and corporate planning levels. The information flow is often blocked between subsystems, therefore continuity becomes difficult to reach. Industry 4.0 vertically integrates the hierarchical subsystems to transform the traditional factory into a highly flexible and reconfigurable manufacturing system, that is the smart factory (Wang et al., 2016). Smart factory combines physical and cyber technology and deeply integrates previously independent discrete systems (Chen et al., 2017). The architecture of a smart factory includes four layers, namely physical resource layer, industrial network layer, cloud layer, and supervision and control terminal layer.

Figure 9 – Smart factory architecture



Source: Wang et al. (2016)

The physical resource layer comprises various kinds of physical artefacts, such as products, machines, and conveyors, which are "smart" thanks to the application of powerful microprocessors and AI technologies. Physical artefacts become smarts in the sense that they not only have abilities of computing, communication, and control (3C), but also have autonomy and sociality. They are autonomous because they control their behaviour and make decisions by themselves. Then, smart artefacts are social as they understand a common set of knowledge and follow a common set of rules for negotiation. Through the industrial wireless network[64] (IWN), smart objects are interconnected with Internet and can communicate with each other becoming able to collaborate and align their behaviours for achieving a system-wide goal.

Industrial network layer forms an infrastructure that not only enables inter-artefact communication, but also connects the physical resource layer with the cloud layer. The industrial wireless network is superior to the wired network ─ such as industrial Ethernet ─ because it can accommodate variations more easily, as it provides more flexible and convenient wireless links. IWN is necessary for a smart factory and its volatile characteristic is due to, for instance, to the newly added machines or the presence of mobile entities like automated guided vehicles. IWN can suitably support the smart factory by implementing IoT; by this means, smart artefacts can communicate and negotiate with each other to implement self-organization and massive data can be uploaded to and processed by the cloud.

Cloud layer is another important infrastructure that supports the smart factory. When operated, smart artefacts composing the physical resource layer may produce massive data, which can be transferred to the cloud through the IWN for information systems to process. The big data analytics then can support system management and optimisation including supervision and control. Storage space and computing ability of the cloud can be scaled on demand thus providing a very elastic solution for big data application. With numerous information systems, like ERP, deployed on cloud and smart things connected to the same cloud, a new world of IoT is created.

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[64] An industrial wireless network (IWN) is a computer network that uses wireless data connections between network nodes. An example of IWN is the wireless sensor network (WSN) that is a collection of distributed sensor devices, communicating wirelessly, which can be used to measure and monitor physical or environmental phenomena such as temperature, pressure, corrosion, vibration, noise, and environmental emissions.

Finally, supervision and control terminal layer links people to the smart factory. With the terminals such as PCs, tablets, and mobile phones, people can access the data and statistics provided by the cloud.

In a smart factory the tangible framework enables a networked world for intangible information to flow freely. This actually forms a CPS where physical artefacts and informational entities are deeply integrated (Wang et al., 2016).

3.3 Green Factory

There is no a widely accepted definition of “green factory” available, nevertheless the common understanding is that the green factory is a firm that operates in an environmentally responsible manner. It aims to provide more economical value with minimized effects on the ecological surrounding (Mueller et al., 2013). To reduce the environmental damage due to the intensive employment of resources, green factories pursue policies designed to decrease the amount of materials and energy used in business operations, and minimize chemical discharge, waste, and air pollution generated through production processes. At the same time, green firms also make comprehensive efforts to prevent environmental risks in advance.

Companies that adopt the circular economy principles belong to the green factories category. In particular, circular economy approach moves beyond the firm level foundations of the resource efficiency and material throughput; indeed, by focusing also on closing the loop of material flow, from a linear to a circular flow, it takes a stance more congruent with the strong environmental sustainability perspective of ecological economics (Loiseau et al., 2016).

Despite some differences between them, sometimes green and sustainable factory are terms used interchangeably. The concept of green relates mainly to environmental issues while sustainability is a wider concept that refers to economic, environmental, and social sustainability (Ramirez-Peña et al., 2020).

Green factories emerge thanks to the firms’ recognition of the urgent need to act in order to reduce the negative impact that industrial companies have on the environment through resources consumption and CO_2 emissions from fuel combustion. To reduce their carbon footprint, more and more companies are implementing initiatives to decarbonize their operations. Moreover, some firms have gone further and started to require their business partners in the supply chain to demonstrate a commitment to decarbonisation as well. The result is a convergence of environmental and economic imperatives that all industrial companies must be prepared to address. The Boston Consulting Group has coined the term "green factory of the future" referring to an ideal production system in which integrated application of decarbonisation measures reduces net emissions to zero (BCG, 2020a).

3.3.1 Green supply chain

Green factories aim at creating green supply chains. A green supply chain can be defined as the "integration of the environmental dimension in the supply chain, including product design[65], procurement and material selection, manufacturing process, product delivery to final consumers and end of life management of the product after its useful life" (Srivastava, 2007). It aspires to reduce the environmental impact of a service or product throughout its life cycle.

Green manufacturers ensure that they are fully aware of their suppliers' and retailers' environmental practices and verify that they comply with a globally acceptable standard. In order to improve their supply chains' greening, often organizations experiment collaborations with suppliers, customers, and even competitors across sectors and geographies. Companies have found that these extra efforts are a high-payback investment, since greener supply chains can deliver benefits for both business and the environment, as they allow resources savings, waste elimination, and productivity improvement.

A company can take various actions to improve the environmental performance of its supply chain. It can:

- Adopt innovative product design and packaging, for instance using a recyclable packaging;
- Enhance sustainability of inputs and suppliers by using raw materials that have a relatively favourable environmental footprint, powering its operations with green energy sources, and favouring suppliers that emphasize renewables.
- Increase efficiency in the use of operational resources. For example, recycling and reusing resources, such as water, consumed in operations.
- Optimise the supply chain network, for instance increasing localized sourcing. This reduces the negative environmental effects of the movement of materials and finished goods across the supply chain.

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[65] Green design denotes designing products with certain environmental considerations. Its scope encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, resource conservation, and waste management (Srivastava, 2007).

- Adopt a Circular Economy model, thus transforming waste into value wherever possible. An example is using material contained in post-consumer packaging to create new ones (BCG, 2020b).

3.3.2 Green manufacturing

Despeisse et al. (2013) proposed specific operational practices which manufactures can employ to become greener. Manufacturing tactics suggested by the authors are structured using the improvement hierarchy which prioritizes options; energy, waste, and resource efficiency hierarchies describe the sequence in which improvements should be implemented. This provides a guide to companies on how to achieve the desired conceptual aim of environmental sustainability at operational level. If possible, firms should start by implementing the most important actions, those at the top of the hierarchies, as they generate the highest environmental benefit. After which, companies should go down the hierarchy also adopting the other green practices.

The material waste hierarchy is typically represented by a pyramid with disposal at the bottom, the last preferred option, rising up though recovery, recycling, reuse, reduction, and finally prevention at the top, the most favoured option.

Energy and low-carbon hierarchies prioritise improvements in energy use avoidance at the top, going down through the levels of technology for energy efficiency and shift to renewable energy sources. Finally, as the last resort, at the bottom of the hierarchy offsetting techniques and carbon sequestration are considered.

Improvement hierarchy for resource efficiency incorporates prevention by avoiding resource use at the top, for instance eliminating unnecessary elements from products; prevention is followed by reduction of waste generation, for example through repairing and maintaining equipment. Then reduction of resource use by improving efficiency is proposed. Possible actions that can be undertaken to fulfil this level of the hierarchy are to optimise production schedule and start-up procedures, and match demand and supply level to reach best efficiency point of use of equipment. Going further down the hierarchy, reuse of waste as resource is suggested, by understanding where and when waste is generated and whether it can be used as resource input elsewhere. Finally, at the bottom there is substitution by changing supply or process, for example adopting renewable and non-toxic inputs or replace technology and resource with less polluting ones (Despeisse et al., 2013).

3.3.3 B Corporation

A concept related to the theme of the green factory is that of the B Corporation. A B Corporation, or B Corp, is a company that voluntary commits itself to act according to the highest standards of social and environmental responsibility. The “B” stands for beneficial and indicates that the certified organization deliberately meets certain levels of transparency, accountability, sustainability, and performance, with the aim to create value for society, not just for traditional stakeholders. Certifying as a B Corporation goes beyond product- or service-level certification; indeed, B Corp certification is the only one that measures a company’s entire social and environmental performance. The certification is issued by B Lab, a global non-profit organization founded in 2006. To be granted and to preserve certification, a firm must receive a minimum score on an assessment for social and environmental performance, integrate its commitment to stakeholders into company governing documents, for example by adopting the legal status of Benefit Corporation, and pay an annual fee. Firms must re-certify every three years to retain their B Corporation status[66].

3.4 Smart Green Factory

The term “smart green factory” refers to a company that applies I4.0 technologies, smart factory, and simultaneously decides to act having a positive impact on the environment, green factory, for example following the principles of circular economy. Indeed, applying the CE principles is only one of the possible ways to practically implement a green approach to the economy[67]. However, for the purposes of this analysis, the focus will be only on companies that decide to become green by implementing the CE approach.

A smart green factory can use I4.0 technologies to support the fulfilment of CE principles. Indeed, as seen in chapter two, technologies can help companies in achieving objectives related to circular economy. In particular, they improve the ability to measure and monitor the use of production inputs, allow traceability of the supply chain and consumption, and

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[66] https://bcorporation.eu/

[67] For instance a company can become green by adopting the ISO 14000, a series of international standards that represent a voluntary tool to improve environmental management within the organization.

ultimately lead to a reduction in the quantity of resources (e.g. energy, water, raw materials, etc.)[68].

3.4.1 Application of CE principles in organisations by means of I4.0: implications for sustainable operations management

Operations management decisions are crucial in contributing to the implementation of the CE principles. Within a smart green factory, I4.0 technologies can represent the basis for a sustainable operations management by means of integrating value chain through data collection and sharing (Stock & Seliger, 2016). Sustainable operations management refers to the integration of the traditional perspectives of efficiency and profit from operations management, with a simultaneous awareness of the environmental impacts of production operations (Kleindorfer et al., 2005).

De Sousa Jabbour et al. (2018) provided a roadmap for organisations to enhance the application of CE principles by means of I4.0 technologies. The authors have considered the ReSOLVE framework, proposed by the Ellen MacArthur Foundation, and linked it to Industry 4.0.

3.4.1.1 The ReSOLVE framework

The Ellen MacArthur Foundation proposed six business actions to guide organizations in implementing the CE principles. The six actions ─ Regenerate, Share, Optimise, Loop, Virtualise, and Exchange ─ together form the so called ReSOLVE framework. Each of the six actions represents a major circular business opportunity which, enabled by the technology revolution, increases the utilisation of physical assets, prolongs their life, and shifts resource use from finite to renewable sources. Every action reinforces and accelerates the performance of the others. The six business actions are:

- *REgenerate*. This is based on a shift to renewable energy and materials. To reclaim, retain, and regenerate health of ecosystems, and return recovered biological resources to the biosphere enables the circulation of energy and materials.
- *Share*. Products should be designed to last longer and maintenance should be available to allow re-use and extension of product life. In this way it is possible to maximise products' utilisation, by sharing them among different users or reusing them through their entire technical lifetime (second hand).

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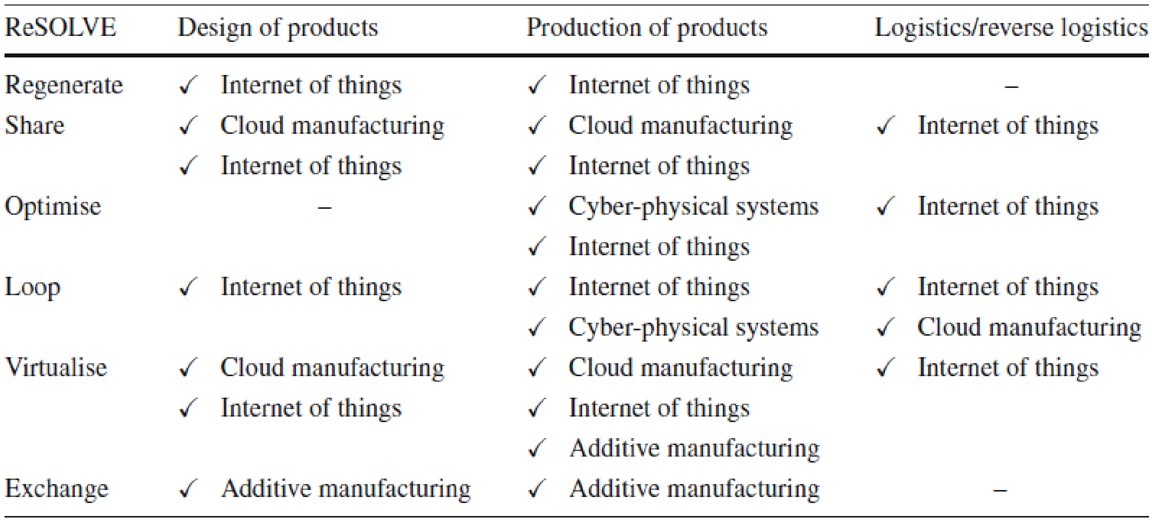
[68] https://www.economia.unipd.it/sites/economia.unipd.it/files/Rapporto_economiacircolare_industria4.0_Legambiente_LMD_2.pdf

- *Optimise*. Increase performance and efficiency of a product and remove waste in production and supply chain ─ from sourcing and logistics, to production, use phase, and end-of-use collection.
- *Loop*. Keep components and materials in closed loops. It means restore the value of post-consumption products and packaging by means of repair, reuse, remanufacture, and recycling.
- *Virtualise*. Dematerialise resource use by delivering utility virtually: directly, for instance books or music, or indirectly, for example online shopping, autonomous vehicles, and virtual offices. This represents a service-focused strategy.
- *Exchange*. This involves substituting old and non-renewable goods for advanced and renewable ones (EMF, 2015).

3.4.1.2 Relationships between CE, Industry 4.0, and sustainable operations management

De Sousa Jabbour et al. (2018) related sustainable operations management decisions to the six business actions proposed by the ReSOLVE framework, and they analysed the I4.0 technologies that could be applicable to each relationship. Sustainable operations management decisions are divided into products design, products production, and logistics and reverse logistics (Gunasekaran et al., 2014). For the analysis, the authors took into consideration four main I4.0 technologies: cyber-physical systems, IoT, cloud computing, and additive manufacturing. The Table 3 summarizes the relationships between CE, Industry 4.0, and sustainable operations management found by the authors.

Table 3 – Relationships between CE, I4.0, and sustainable operations management



ReSOLVE	Design of products	Production of products	Logistics/reverse logistics
Regenerate	✓ Internet of things	✓ Internet of things	–
Share	✓ Cloud manufacturing ✓ Internet of things	✓ Cloud manufacturing ✓ Internet of things	✓ Internet of things
Optimise	–	✓ Cyber-physical systems ✓ Internet of things	✓ Internet of things
Loop	✓ Internet of things	✓ Internet of things ✓ Cyber-physical systems	✓ Internet of things ✓ Cloud manufacturing
Virtualise	✓ Cloud manufacturing ✓ Internet of things	✓ Cloud manufacturing ✓ Internet of things ✓ Additive manufacturing	✓ Internet of things
Exchange	✓ Additive manufacturing	✓ Additive manufacturing	–

Source: de Sousa Jabbour et al. (2018)

IoT can be used in design and production of products to support the Regenerate action. Indeed, design and production decisions on sustainable operations management can be adapted based on data provided by sensors. Intelligent assets are reshaping humans' ability to manage the Earth's natural capital. In particular, IoT driven insights into the complex dynamics of natural resources allow conventional agricultural systems to significantly increase asset productivity while simultaneously enable the regeneration of land. Real time data collected thanks to IoT allow to plan, monitor, and control factors related to land management. This gives farmers the possibility to regenerate areas of their land which are at risk of degradation, reduce resource consumption (water, nutrients, energy, etc.), and improve the productivity of harvests. For instance, IoT allows to automate irrigation systems based on weather conditions in real time, and to manage the use of pesticides according to the health of plantations (EMF, 2016).

Cloud manufacturing and the IoT make possible to implement the Share strategy. These technologies enable organizations to collect information on demand and consumers' behaviour. Therefore organisations can more easily manage the assets sharing ─ for instance cars or appliances ─ and improve both product and service design for better utilisation or replacement of equipment. Moreover, being able to monitor the condition of the product, companies can extend products' life spans, for example by doing maintenance before the component breaks, and this increases the possibility of reuse the product (second hand). The design, production, and logistics decisions of sustainable operations management can be adaptable, based on the data provided by the resources of cloud manufacturing and the Internet of Things (de Sousa Jabbour et al., 2018).

The Optimise action can be supported by cyber-physical systems and the IoT, that can collect data on which to base the production and logistics decisions of sustainable operations management. Optimise is a technology-centred strategy. Organisations can use digital manufacturing technologies, such as sensors, automation, RFID, and big data to reduce waste in production systems and increase their efficiency. Thanks to sensors embedded in the equipment, several actions are taken. For instance, it is possible to identify failures, which might create waste; or it is feasible to asses machines efficiency and intervene immediately if improvement are possible, thus avoiding excessive use of resources, and ultimately optimise also delivery routes. In addition, IoT captures real-time data of logistics resources, which are shared among companies after the value-added processes, thus facilitating the process of reverse logistic (Liu et al., 2018).

Following the CE principles, design, production, and logistics decisions should be adapted to extend the circularity of materials and energy, and implement the Loop action. The Industry 4.0 technologies which could support the Loop approach are the IoT, cyber-physical systems, and cloud manufacturing. A product should be designed to include sensors informing the users of the components and materials contained in it. This greatly facilitates the disassembly and recycle processes at the end of the product's useful life and favours a correct waste disposal. In addition, data collected by IoT can improve production decisions by favouring the reuse of resource consumed in operations, like water, within the manufacturing processes. Moreover, IoT can enhance logistics and reverse logistics since it allows to track post-consumption products and packaging, so that their components can be reused, remanufactured, or recycled (de Sousa Jabbour et al., 2018). Cloud manufacturing could support organisations in implementing the Loop action by finding buyers for reused or refurbished components (EMF, 2016).

The Virtualise action is focused on offering services rather than physical products. Cloud manufacturing and the IoT enable to design better services since they allow a continuous connection between organisations, suppliers, and customers. For instance, information on consumers' behaviour can be used to develop services based exactly on customer's needs, hence increasing customers satisfaction. In addition, virtualize action can be advanced by using additive manufacturing. Indeed, 3D printers rely on digital projects and prototypes, thus avoiding the creation of the latter in the physical world and the related resource consumption.

Finally, the Exchange action can be supported by additive manufacturing, as more and more renewable 3D printing material are created. For instance PLA (Polylactic acid) is derived from renewable resources; it is bio-based, as material is derived from biomass, and biodegradable. Furthermore, PLA is a thermoplastic, meaning that it can be melted and reshaped without significantly degrading its mechanical properties. Hence, PLA is mechanically recyclable[69].

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[69] https://bioplasticsnews.com/2019/07/02/all-you-need-to-know-about-pla/

Taking into consideration these relationships, de Sousa Jabbour et al. (2018) have developed a roadmap for organizations which want to move toward CE adopting Industry 4.0 technologies. The path includes five steps.

First of all, the company has to select which actions of the ReSOLVE framework are suitable to its production processes and purpose.

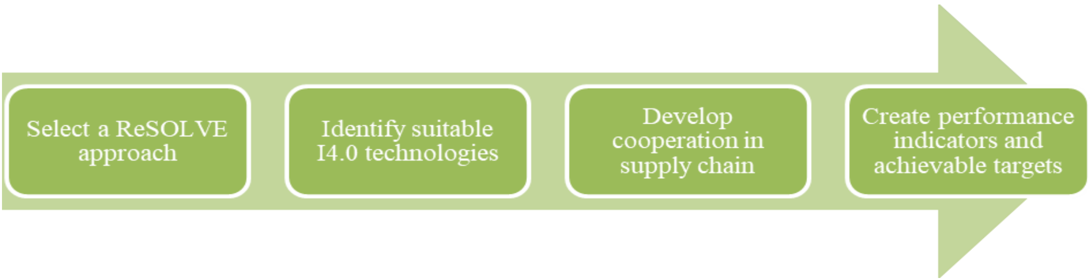
Second, assisted by the Table 3, the firm has to identify the I4.0 technologies that can support the selected CE actions and those that, at the same time, are feasible for it, considering factors such as availability, costs, and technical constraints.

The third step for the organisation is adapting sustainable operations management decisions for the design, process, and logistics of products. The change depends on the first step, since the selected ReSOLVE approach would impact the tracking, tracing, and managing of post-use products and packaging, from the conceptualisation to the development of products, the latter including extended product life cycles.

The fourth step consists in developing collaboration in the supply chain. The integration among tiers in supply chains is required in order to connect technologies and resources and share information pertaining to demand, supply, deliveries, and customers' behaviour in real-time.

Finally, the fifth step for organisations is the creation of performance indicators and small and achievable targets in order to measure progress towards the CE.

Figure 10 – A roadmap for organisations to enhance the application of CE principles by means of I4.0 technologies



Source: adapted from de Sousa Jabbour et al. (2018)

3.4.2 Benefits of being a Smart Green Factory

Companies can obtain many benefits from integrating the CE and I4.0. Indeed, factories adopting both the approaches can enjoy positive effects generated both by the implementation of CE practices, and the exploitation of smart factory technologies. In particular, I4.0 technologies themselves provide benefits to companies, but at the same time, as seen in chapter two, they also help firms in obtaining benefits related to circular economy application, since they support the implementation of the CE principles. Several circular benefits can be achieved leveraging on I4.0 technologies. The main are the ability to monitor the use of productive inputs, traceability of the value chain, reduction of production inputs, adoption of sustainable materials, reduction of environmental impacts, use of secondary raw materials and scrap materials of other firms, reuse of scrap materials from firm's activities in its own productive cycle, and waste reduction.

3.4.2.1 Industry 4.0 benefits

The adoption of I4.0 technologies can bring several different benefits to companies. Undertaking a smart factory journey can lead to:

- *Increased productivity*. Via the use of cyber-physical systems, which allow the observation of processes in real-time, it is possible to improve material consumptions and optimise processes (in speed or yield), thus resulting in an increase in productivity (Blunck & Werthmann, 2017). Moreover, the application of I4.0 technologies also enables an improvement of labour productivity. For instance, they make it possible to reduce waiting times between different production steps in manufacturing and decrease the burden or complexity of tasks executed by workers, thus increasing the speed of manual production phases. An analysis made by McKinsey & Company[70] shows that I4.0 technologies lead to 3-5% increase in resource and process productivity and 45-55% increase in labour productivity in technical professions (McKinsey & Company, 2015).
- *Enhanced assets efficiency*. Digitalization in manufacturing can deliver many innovative capabilities to firms, through greater connectivity, more flexible automation, and increased data. In particular, data collection and analysis allow assets to self-correct[71], hence yielding increased efficiency. This translates into lower asset downtime, optimised capacity, and reduced changeover time (Lee et al., 2015). McKinsey & Company has found that the use of predictive maintenance enables to decrease total machine downtime by 30-50% and to increase machine life by 20-40% (McKinsey & Company, 2015).

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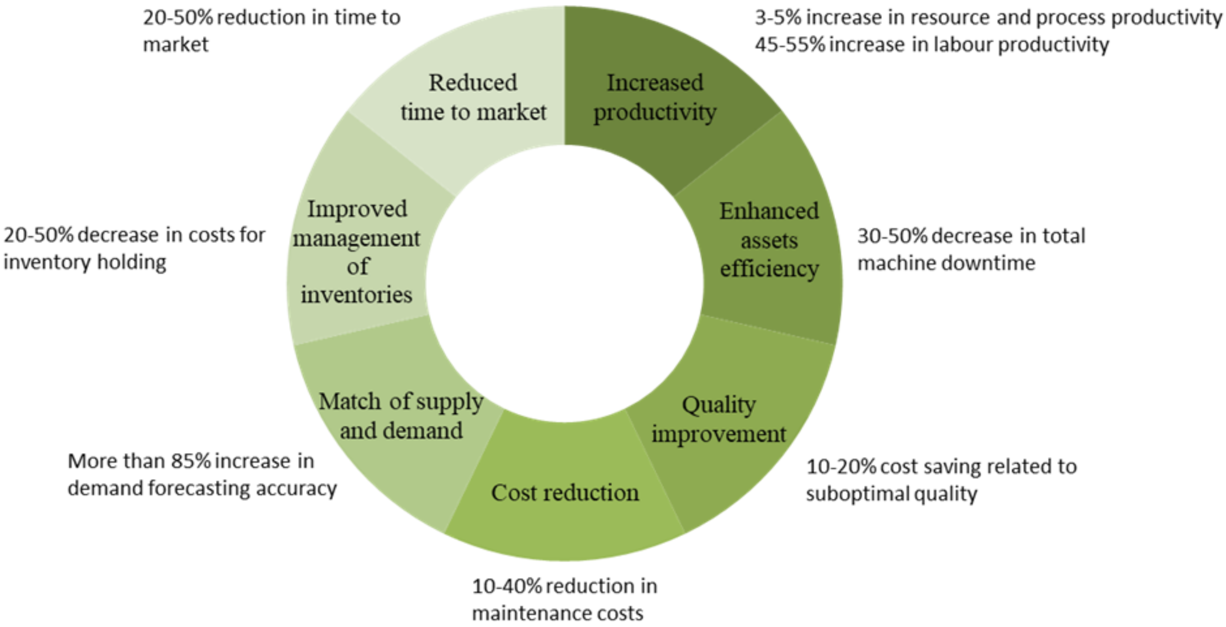
[70] McKinsey & Company carried out a global Industry 4.0 survey of 300 experts from all relevant industries. The survey was based on 21 questions and allowed different types of answers such as importance and significance-rating questions as well as ranking questions. The B2B panel was held in the US, Germany, and Japan in January of 2015, with 100 companies per country of which each had at least 50 employees.

[71] This is what distinguishes the smart factory from traditional automation.

- *Quality improvement.* Through real-time process monitoring, smart factory can predict and detect quality defects sooner, and can help to identify causes of poor quality. Reaching quality standards ensures customers satisfaction while avoids necessity for rework and consequently extra costs (Deloitte, 2017). By using I4.0 technologies a saving of costs related to suboptimal quality of about 10-20% can be achieved (McKinsey & Company, 2015).
- *Cost reduction*. IoT increases cost transparency and this allows to enhance costs management (Kiel et al., 2017). A better-quality process, reached through its real-time monitoring, leads to more cost-efficient process and a better-quality product, that may also mean lowered warranty and maintenance costs. In addition, product manufacturing can be more cost effective, when machines get a longer operational time. For example, this can be made possible through remote maintenance that carries out error diagnosis and even repair without the necessity of a technician visiting the site. Reduction in maintenance costs due to remote and predictive maintenance varies between 10 and 40% (McKinsey & Company, 2015).
- *Match of supply and demand.* A perfect understanding of customer demand in terms of quantity and product features leads to a much better predictability through new possibilities, like crowd forecasting based on advanced analytics. In addition, this prevents storage cost and waste by unnecessary inventory. From McKinsey & Company's analysis it emerges that I4.0 technologies can increase the accuracy of demand forecasting to more than 85% (McKinsey & Company, 2015).
- *Improved management of inventories.* Too much inventory leads to great capital costs and so this must be avoided through a proper management of inventories. By applying I4.0 technologies, drivers of excess inventories, like overproduction or unreliable demand planning, can be targeted. Systems which automatically reorder if necessary reduce costs for inventory holding by 20-50% (McKinsey & Company, 2015).
- *Reduced time to market.* New technologies emerging with Industry 4.0 enabling faster and cheaper R&D processes; for instance concurrent engineering or rapid prototyping can be reached by using 3D-printing which can significantly reduce the time to market (between 30 and 50%).

Smart factory benefits emerged from the analysis of McKinsey & Company (2015) are summarised in Figure 11.

Figure 11 – Smart factory benefits



Source: adapted from McKinsey & Company (2015)

3.4.2.2 Circular Economy benefits

Businesses may benefit significantly by shifting their operations in line with the principles of the circular economy. These benefits include financial and non-financial benefits.

Main benefits are:

- *Cost savings*. CE allows decrease costs as it lowers virgin-material requirements, for example due to parts recovery or virtualization. The Ellen MacArthur Foundation estimated that, in the medium-lived complex products industries, the CE represents net material cost savings at an EU level of up to USD 630 billion annually (EMF, 2015). Furthermore, CE reduces costs by improving product's efficiency, removing waste from supply chains, prolonging product life spans through maintenance and design, and keeping components and materials in "closed loops" through remanufacturing and recycling — therefore allowing to save money for new materials and the creation of new products (McKinsey & Company, 2017). In addition, recycling, recovery, and remanufacturing enable to significantly reduce waste disposal costs. Moreover, cost savings are also generated thanks to companies shifting to renewable energy and materials avoiding spending a lot for scarce resources, including fossil fuels.
- *Increased revenues.* The product lifecycle extension practice allows companies to maximize value beyond the point of sale, generating additional revenue from assets. Goods that otherwise would be lost through wasted materials are instead maintained or

even improved by repairing, upgrading, remanufacturing, or remarketing products[72]. In addition, an increase in sales may be activated by the green turning-point of the company, which nowadays may also attract more and more consumers. A more efficient use of resources, promoted by the circular economy, makes sense both from an environmental sustainability perspective, and as financial terms. Indeed, better use of resources (energy, materials, water, and waste) goes hand-in-hand with improved cost control and increased profitability, as well as encouraging more innovative ways to grow productivity and create value (Institute for Manufacturing, 2019).

- *Reduced volatility and greater security of supply.* Shift to a CE means using less virgin material and more recycled inputs, reducing a company's exposure to ever more raw materials prices and increasing resilience. In addition, it reduces the threat of supply chains being disrupted. Risks ─ including disruption from floods, droughts, interruption of energy supply, and of the availability of materials ─ are currently increasing due to a combination of climate change and geopolitics. One way of mitigating such disruptions is to reduce the resources required per unit of value added. The improved resources productivity driven by CE can help to achieve this goal (Institute for Manufacturing, 2019).
- *New demand for business services.* A CE would create demand for new business services such as collection and reverse logistics companies which support end-of-use products being reintroduced into the system, or product remarketers and sales platforms that facilitate longer use and higher utilisation of products, as well as parts and component remanufacturing offering specialized knowledge.
- *Improved customer interaction and loyalty.* Within the circular framework, interaction with customer doesn't stop with the product's sale, but continues in the post-sale for the purpose of recovery, recycling, or remanufacturing materials embedded in the product. In addition, new business models aimed to enhance product utilization, like rentals or leasing contracts, establish long-term costumer relationship, as the number of touchpoints increases over the product's lifetime. As a result, companies can have a unique insight into usage pattern that can lead to improved products, better services, and higher customer satisfaction[73].
- *High innovativeness.* The aspiration to replace one-way products with goods that are "circular by design" and create reverse logistics networks and other systems to support

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[72] https://www.greenbiz.com/article/how-circular-economy-unlocks-new-revenue-streams

[73] https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail

the CE is a powerful spur to new ideas. This can represent more profit opportunities for companies (EMF, 2013).

- *Improved corporate reputation.* Companies oriented towards environmental sustainability generally collect positive feedback; greater attention to the environment and to future generations can fuel enterprises' reputational capital, strengthening their competitive positioning.
- *Brand repositioning (differentiation).* Companies are using the circular approach to differentiate themselves from competitors. Basing on quality, durability, and environmental-friendliness, firms are improving their competitive advantage by capturing a larger market share.

Despite financial benefits rising from CE practices implementation, in particular cost saving and the increased revenues, the main motivation for which firms decide to adopt CE principles is not represented by these benefits. A research conducted by Legambiente and the Digital Manufacturing Lab of the University of Padua[74] found that the first reason that leads companies to adopt a circular economy model is the ethics and corporate social responsibility. The reduction in production costs, instead, is in eighth place among the motivations[75]. This shows a strong social orientation of companies which increasingly decide to act not only looking at their interests, but also at needs of the environment and of the society.

3.4.3 Challenges for a Smart Green Factory

It is important to underline that becoming a smart green factory is a process that presents various challenges for an organization. Some of the main barriers to the implementation of I4.0 technologies are the lack of necessary competences, concerns about cybersecurity, difficult coordination of actions between the different organizational areas, and reliability of connectivity between machines (McKinsey & Company, 2016). Rajput and Singh (2019) identified the need for integrating CPSs as one of the major I4.0 challenges. Indeed, CPSs use different computing models and collect heterogeneous data which must then be analysed together. Therefore, uniform standards and CPS' specifications are needed. An industry 4.0 factory works intelligently with smart devices able to capture data, detect errors and failures;

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[74] In 2017, Lagambiente and the Digital Manufacturing Lab of the University of Padua started a joint study on Italian businesses that practiced the circular economy to investigate the motivations, results achieved, and difficulties of the transition process.

[75] https://www.economia.unipd.it/sites/economia.unipd.it/files/Rapporto_economiacircolare_industria4.0_Legambiente_LMD_2.pdf

however, different factories require the development and configuration of different smart devices, which need large investments and time before being implemented, hence representing a challenge for companies. Leitão et al. (2018) figured out some I4.0 barriers related to design, compatibility, and infrastructure standardization. These challenges are due to the complexity of designing an infrastructure that can handle computational intensive tasks and develop self-adaptation functionality, while integrating heterogeneous devices and components in automation systems. Compatibility refers to the need to keep the system's components working together in a functioning environment without implementing any changes to the systems.

Specifically concerning barriers to adopt the CE model, Preston (2012) identified the following: high up-front costs, complex international supply chains, resource-intensive infrastructure lock-in, failures in company cooperation, and lack of consumer enthusiasm. Indeed, customers often show little willingness to give values to efforts made in terms of circular economy and to reward them through a higher price of "circular" products and services. Moreover, Bicket et al. (2014) observed other challenging factors for CE implementation like an insufficient investment in technology, a lack of economic signals that encourage efficient resource use, a pollution mitigation or innovation, and limited sustainable public incentives. Furthermore, Rizos et al. (2015) listed additional barriers for companies to adopt a circular approach, namely environmental culture, lack of effective legislation, information deficits, and relatively low technical skills.

CHAPTER 4
ANALYSIS OF CIRCULAR ECONOMY AND INDUSTRY 4.0 IN ITALY

4.1 Introduction

In this chapter, real cases of companies that practice the circular economy will be analysed. Starting from the firms' general characteristics, the initiatives undertaken by them on the circular economy theme will then be described. Subsequently, the I4.0 technologies adopted will be listed explaining how these help the companies in the fulfilment of the circular economy principles.

4.2 The aim of the analysis

The objective of the study is to investigate how within the selected companies, the technologies of Industry 4.0 contribute in meeting the principles of circular economy. Some of the Italian companies that Confindustria has classified as "Excellence in the circular economy"[76] are used for the analysis. Companies were interviewed in order to examine their circular economy projects and the I4.0 technologies adopted, and understand if, and if so how, the latter support the implementation of circular economy projects ─ for which firms have been classified as excellences of CE ─ and, more widely, the CE principles. In the Appendix it is possible to find the questions that were used as guidelines for the interviews.

4.3 The sample used for the analysis

The focus of the analysis is on Italian firms classified by Confindustria as "Excellence in the circular economy" and belonging to some of the typical sectors of Made in Italy, that is paper, furniture, and mechanical. Specifically, the companies analysed are Lucart S.p.A., Reno De Medici S.p.A., Icma S.r.l. (paper industry), TM Italia S.r.l. (furniture industry), and Gusbi S.p.A. (mechanical industry). The main information about the firms analysed are summarised in Table 4.

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[76] http://economiacircolare.confindustria.it/case-history-scopri-le-eccellenze-delleconomia-circolare/

Table 4 – Data about companies of the sample

Name of the company	Industry	Number of employees (in 2019)	Revenues (in 2019)	Headquarter location
Lucart S.p.A.	Paper	1611	€ 515,000,000	Porcari (LU), Tuscany
Reno de Medici S.p.A.	Paper	430	€ 223,041,000	Milan (MI), Lombardy
Icma S.r.l.	Paper	40	€ 6,515,100	Mandello del Lario (LC), Lombardy
TM Italia S.r.l.	Furniture	25	€ 3,900,000	Campolungo (AP), Marche
Gusbi S.p.A.	Mechanical	27	€ 10,350,690	Vigevano (PV), Lombardy

Source: Interviews with companies

Each of these companies will now be analysed in detail, examining the circular economy project promoted, the technologies adopted, and how the latter contribute to the former, or more generally to the fundamental principles of the circular economy.

4.4 Lucart S.p.A.

Lucart is a Tuscan multinational firm leader in Europe in the production of MG paper, tissue products (paper items for daily use such as toilet paper, kitchen paper, napkins, tablecloths, handkerchiefs, etc.), and airlaid products. The company, founded in 1953 in the province of Lucca, today owns nine production plants (five in Italy, one in France, one in Hungary, and two in Spain) and a Logistic Center in Italy. The company's production activities are distributed over three business units, namely Business to Business, Away from Home, and Consumer, operating in the development and sales of products with brands such as Lucart Professional, Tenderly Professional, Fato, and Velo (Away from Home area), and Tenderly, Tutto, Grazie Natural, and Smile (Consumer area)[77].

Starting from the awareness that the Planet's natural resources are limited, Lucart has always acted to extend materials' useful life, and recover them to create new products in a continuous cycle. Assocarta[78] found that in Italy, each year, approximately 1.5 million tonnes of tissue paper are produced for hygiene and sanitary use, of which only 7% comes from recycled materials. Lucart goes completely against this trend in the industry, as 55% of the raw

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[77] https://www.lucartgroup.com/

[78] Assocarta is the trade organisation working on behalf of the Italian Paper Industry representing pulp, paper, and board manufacturing companies in Italy.

material it uses is recycled. The company boasts various environmental certifications, including multi-site certification FSC®[79] and the EU Ecolabel[80].

In 2010, Lucart was the first company to launch a circular economy project in the field of "tissue" paper. In collaboration with Tetra Pak®, with the launch of the Natural project it has transformed what was waste for a production or consumption cycle, into new raw material for other production cycles, creating economic, social, and environmental value. With Natural, the company has given new life to tetra pak type beverage cartons. A machine, called pulper, minces the tetra pak cartons, then water is added and the different tetra pak's components ─ cellulose fibres, aluminium, and polyethylene ─, having different weights, separate. From cellulose fibres Lucart creates Fiberpack®, with which it produces paper EU Ecolabel and FSC Recycled[81] certified. From aluminium and polyethylene, instead, it produces Al.Pe.®, the new raw material used for the production of dispensers, that are used to dispense toilet paper or paper towels in public toilets, and the manufacture of pallets for the transportation of its own goods. Moreover, Al.Pe.® is used also by manufacturing industries for numerous uses, from constructions to urban furniture to the Venice mooring poles. The Figure 12 depicts the process carried out within Natural.

Therefore, with the Natural project, Lucart is able to recover all beverage carton's parts, fibrous and not, and transform them into value, thus significantly reducing waste. In addition, paper recycling allows to maximize the utilization of natural resources used in its production, in this case wood and water. Furthermore, water used in the production process can be used over and over again thanks to the presence of purifiers inside the Lucart's factories.

Natural was a challenging project for Lucart because the company, used only to process waste coming from typography companies, no longer had to manage only an industrial by-product, but also what was a domestic waste[82].

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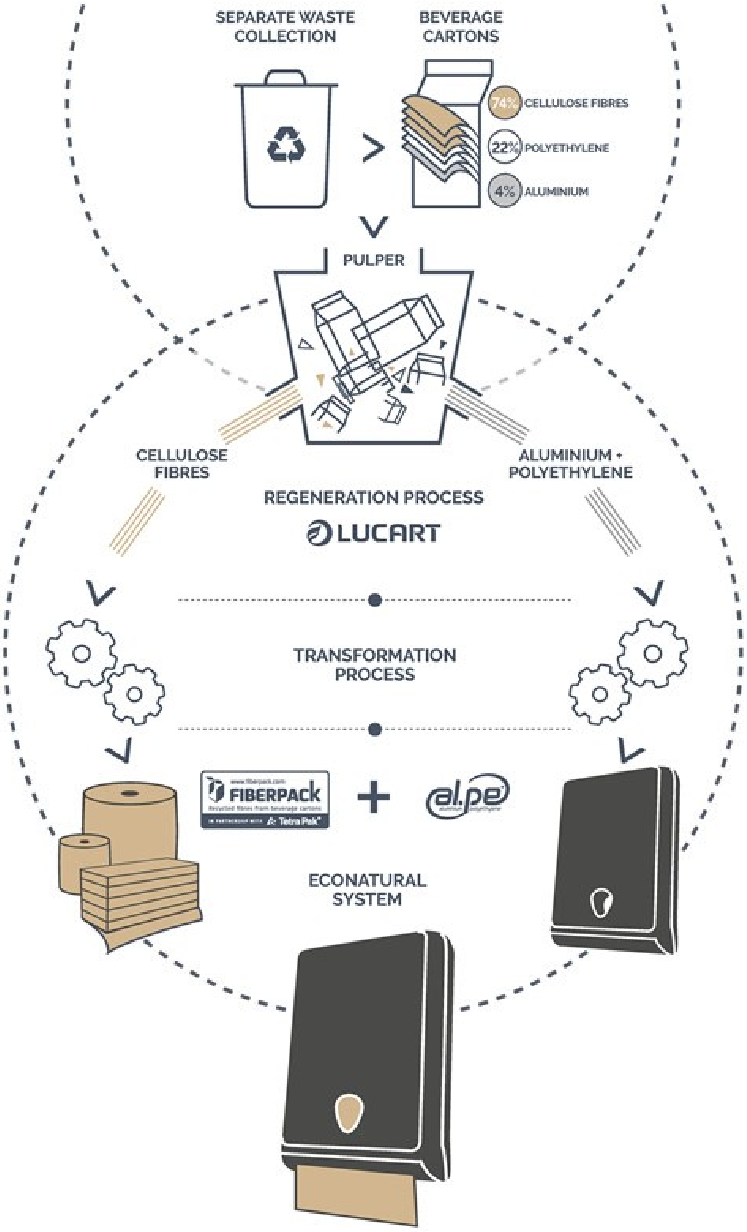
[79] FSC® certification ensures that the raw material used to make a wood or paper product comes from forests managed in a responsible way according to strict environmental and social standards.

[80] EU Ecolabel is a European label used to certify the reduced environmental impact of products or services offered by companies that have obtained its use. In the paper sector, the certification promotes the choice of cellulose fibres coming from certified sources and of selected suppliers, who make use solely of sustainable forest management techniques.

[81] FSC Recycled label indicates that all the wood or paper in the product comes from recycled material, of which at least 85% post-consumer. Unlike general "recycled" claims, which require no verification, the FSC Recycled label provides assurance that all the material in a product has been verified as genuinely recycled.

[82] http://economiacircolare.confindustria.it/ch/lucart-spa/

Figure 12 – Natural, Lucart's circular economy project



Source: Lucart Professional's website[83]

Thanks to the Natural project, Lucart is now able to offer a product made from 100% recycled paper, which is transported on a recycled pallet, and used through a recycled plastic dispenser. This model of product development fully respects the principles of circular economy, which starts from the valorisation of waste through proper disposal, and continues up to the point in which they have been fully transformed into secondary raw materials that are ready to be re-used and marketed[84]. Additionally, the dispensers would in turn be technically 100%

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[83] https://www.lucartprofessional.com/en/greece/lucart-export/innovations/econatural/

[84] https://www.lucartgroup.com/

recyclable, but there is still no network that allows to recover and recycle them. In fact, in Italy there is a recycling system — that of separate collection of waste — only for plastic packaging, but dispensers are not classified for packaging.
In the 2013-2019 period, Natural project has contributed to recover more than 5.4 billion beverage cartons, avoid using of more than 2.3 million of trees, and prevent more than 141,000 tons of CO_2 emitted into the atmosphere[85].

In 2015, Lucart launched a pilot project in Slovenia along with a number of local partners with the goal of developing a circular economy system in the urban area of Novo Mesto that would be long-lasting and replicable internationally. In this pilot system, Lucart and a local distributor worked together with public schools, municipal facilities, and waste management and selection companies to recover and process beverage cartons into new paper products for hygienic and sanitary use within the same municipal facilities and schools where waste was collected.

Figure 13 – Material flow cycle of beverage carton in Novo Mesto, Slovenia

Source: Lucart's Sustainability Report 2019

For Lucart, be circular means also being involved in industrial symbiosis. Indeed, the company is symbiotic to graphic paper industries as it mostly uses recycled paper which generally comes from the industrial scraps of the typography companies. The firm is now studying whether there are industries that are symbiotic to it, which could therefore reuse its waste. The two main waste families resulting from the paper recycling process are the paper

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[85] Lucart's Sustainability Report 2019. Available at: https://www.lucartgroup.com/sfogliabili/rapporto-sostenibilita-eng-2019/mobile/index.html#p=52

mill sludge, which is the fibrous part that cannot be reused by the company to make its paper type, and the so-called pulper waste which is instead the part of plastics, metals, and so on, that can be contained in the raw materials Lucart uses and which do not become paper. The paper mill sludge has cellulose fibres and minerals and could be used, for example, as soil improvers in agricultural land and nursery crops, or to produce energy, as they are biomass. However this process can only be done abroad, as in Italy it is not permitted due to the lack of political and citizens will to produce energy in this way. For what concerns the second type of waste, the pulper one, this could be used for the creation of plastic products.

Regarding the use of renewable energy, Lucart has installed in Italy several photovoltaic panels. Despite this, the amount of renewable energy produced by the company represents a small percentage of the total energy used. In 2019 the electricity produced from renewable sources represented only 0.08% of the total energy consumption for that year[86]. Regrettably, in a paper mill the energy must be given in a continuous way ─ as the machines work 24 hours a day, 7 days a week ─ and renewable energies, especially solar, but also wind, do not guarantee endless continuity. To cover their energy needs through photovoltaic panels it would be necessary to cover an area as large as the entire Po Valley. For this reason, Lucart uses mainly new generation methane gas turbines in cogeneration ─ producing electricity and heat.

4.4.1 I4.0 technologies in Lucart and their role in implementing CE principles

In Lucart, Industry 4.0 technologies are widely present in logistics, while they are scarcely present in the paper mill and the transformation part ─ starting from the reel made in the paper mill which is divided, unrolled, and printed. In fact, for example within the Natural project, the manufacturing process of recycled paper begins with the separation of the materials contained in the tetra pak which, as seen before, takes place through a physical process, and so without the use of advanced technologies, such as the optical recognition of materials.

Within Lucart's production plants, new generation machines are connected to Internet and each other. IoT plays an important role in Lucart: it allows to collect a huge amount of real-time data that the company uses to monitor the functioning of the equipment. This enables to optimize resource consumptions and therefore guarantee the production of high quality paper

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[86] Lucart's Sustainability Report 2019. Available at: https://www.lucartgroup.com/sfogliabili/rapporto-sostenibilita-eng-2019/mobile/index.html#p=52

with minimum energy and water use. In addition, thanks to IoT, it is possible to do remote assistance; in case of functioning problems, machines send a signal to the maintainer who can remotely suggest to the company the proper intervention. This avoids the resource consumption and GHG emissions related to the travel of the technicians required in the case of on-site maintenance.

New generation equipment are able to do a self-diagnosis, detect problems and if so stop. As a consequence, machine can be repaired before excessive use of energy occurs or components break, thus extending their lifecycle. The product's quality control takes place through high-speed cameras installed in the machines which, during the production process, collect images on the material, which are then processed by artificial intelligence capable of detecting errors and flagging them promptly. By identifying exactly the reel's portion containing defects, AI allows to discard only that part, minimizing waste.

For what concerns the design phase, Lucart uses simulation in order to calculate the environmental impact of its products and find the most environmentally friendly solution.

At the end of the Lucart's production processes, dual-arm robots palletize goods. After the pallet is created, a machine analyses its shape to verify that it is made in the right way. Machine decides whether the pallet can proceed or not, thus preventing the shipment of "wrong" pallets. In this way there are no pallets sent back to be corrected, and therefore the consumption of resources and the emissions related to additional transport are avoided. Once approved, the pallet is transported to the warehouse by an automated guided vehicle (AGV) using laser technology capable of interacting with the surrounding environment. Autonomous robots and the AGV deployed in these phases maximize processes efficiency and minimize errors thus resulting in a large resources saving.

The production plant in Diecimo and the logistics centre in Altopascio, both in the Lucca province, are, in Lucart Group, the most advanced plants with regard to I4.0 technologies because of the presence of CPSs, in particular automated warehouses. In 2017, Lucart launched the LOGICA project with the aim to create a fully automated logistics centre that improves the efficiency of the logistics process and frees warehouse resources in the Diecimo plant, eliminating possible obstacles to increasing production[87]. For this purpose, leveraging on RFID, IoT, and cloud technologies, Lucart has developed a logistics center in Altopascio equipped with an automated warehouse, like the one created at the same time in the Diecimo plant.

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[87] Expanding the Diecimo plant would have been impacting from a landscape point of view.

In the Diecimo plant, the robot that wraps the pallet communicates with an AGV which picks up the pallet, knows if this must be sent to Altopascio plant or must be stored in Diecimo warehouse, and moves it in the plant accordingly. Then, when they reach the amount needed to completely fill the truck, goods destined to Altopascio are loaded in the vehicle by automatic roller conveyors in just 90 seconds, and not the traditional 30 minutes required for manual loading. Finally, the transport document is automatically generated and the truck driver can view it in his smartphone; then the driver goes to the factory exit where the RFID hardware automatically reads the tag on the truck and allows it to exit. In just half an hour the vehicle arrives at the logistics hub where the reverse process is carried out. The RFID technology allows automatic traceability of warehouse goods loaded and picked up.

The platform that manages the logistic process is then integrated with business management systems, like ERP, enabling a seamless information flow throughout the whole organisation. The integration of data of the Diecimo plant and the logistic hub allows to know exactly the amount of products present in each of the two sites, thus avoiding wasteful duplication and redundant production.

The I4.0 technologies involved in the LOGICA project enabled the company to greatly enhance the efficiency of the logistics and simultaneously helped Lucart in the achievement of the circular economy objectives. Indeed, RFID technology, that allows to track and manage inventories, always guarantees the loading of the right products into the truck, consequently reducing unnecessary transportation, and also reduces fuel usage, related to shipping errors. At the same time, smart robots managing the loading of the truck ensure that it is loaded with the highest possible accuracy, thus giving the possibility to always fill the truck up to reach its maximum capacity; this enables to maximize the use of resources employed in transport. Moreover, the creation of a logistics hub makes it possible to organize the company's shipments always at maximum transport efficiency and the use of its own vehicles allows Lucart to control the emissions produced during the trip. Furthermore, the company has activated a progressive replacement of Euro 5 vehicles, used for the transport between the two plants in the province of Lucca, with new generation vehicles powered by LNG (Liquefied Natural Gas); in 2019, 50% of the trips were carried out with LNG trucks avoiding the release of 7 tons CO_{2eq} into the atmosphere[88].

The Table 5 summarises the role of I4.0 technologies in implementing CE principles inside Lucart.

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[88] Lucart's Sustainability Report 2019. Available at: https://www.lucartgroup.com/sfogliabili/rapporto-sostenibilita-eng-2019/mobile/index.html#p=52

Table 5 – I4.0 technologies in Lucart and their role in implementing CE principles

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	Increase in logistics' efficiency, reduction in error rate, and trucks' load always to their maximum capacity enabled by automated warehouse.	Better maintenance decisions thanks to data provided by machines connected as a network.		
Internet of Things (IoT)	Real-time monitoring of material, energy, and water consumption, detecting inefficiencies; elimination of technicians' travel through remote assistance; goods' traceability.	Reduction in damages to machine' components through real-time data about machine allowing operators to intervene promptly in case of malfunctioning.		
Big data and analytics	Increase in efficiency of production process and water purification process.	Proper maintenance and repair of machine, lengthening its life cycle and favouring the reuse.		
Cloud computing	High degree of server utilization; lower energy consumption.	Storage of data used for improving maintenance decisions.		
Simulation		Assessment of product life cycle.		
Artificial intelligence (AI)	Precise identification of the reel's portion containing defects; elimination of unnecessary transports due to shipment of defective products.			
Autonomous robots	Reduction in error rate; elimination of additional transports due to wrong shipments.			
Horizontal and vertical system integration	Elimination of wasteful duplication and redundant production; better raw material supply.			

Source: own elaboration

4.5 Reno De Medici S.p.A.

Reno De Medici Group is the second largest European producer of coated recycled cardboard, the largest in Italy, France, and the Iberian Peninsula. RDM Group, born in 1967 in the Bologna province, today represents over 95% of the European production in its sector. Internationally, it has a strategic presence thanks to its seven manufacturing plants ─ three in Italy, two in France, one in Germany, and one in Spain ─ and two sheeting centres, and a sales network active in 70 countries.

For RDM, environmental sustainability is a very important corporate value; since 2017 the Group has implemented an internal function dedicated to sustainability and risk management which is committed to increasingly reducing the Group's environmental impact. Reno De Medici gives new life to cellulose fibres derived from the recovery and recycling of urban waste of paper and cardboard (75%) or residues from the industrial and commercial sector (25%). About 98% of the paper that is collected is transformed into a new product. RDM is a very large Group which transforms about 1 million tons of paper from recycling every year. Considering that a European citizen produces on average about 70 kg of paper and cardboard waste per year, RDM therefore transforms the equivalent of 14 million inhabitants. The plastic waste that derives from the cleaning of material from urban waste collection does not end up in landfills, but in waste-to-energy plants for energy production.

The Group offers products that are recycled, and in turn over 90% recyclable and biodegradable, feed the RDM Group's circular business model[89]. Indeed, cellulose fibres, before deteriorating, can be recovered and recycled up to 6-7 times, thus extending the life cycle of this resource. Only one paper mill in France, for market needs[90], produces virgin fibre cardboard. In this case, virgin raw materials utilized come from responsible resources; purchased wood raw materials and virgin fibres are FSC® or PEFC™ certified. In addition, on the total material that RDM uses for producing its cardboard, 84% comes from renewable resources.

In Reno De Medici, circularity is also present in the field of wastewater management. Production process of paper and cardboard requires the use of important water resources; RDM owns water purification systems in all its plants that allow it to reuse the water withdrawn in multiple processing cycles.

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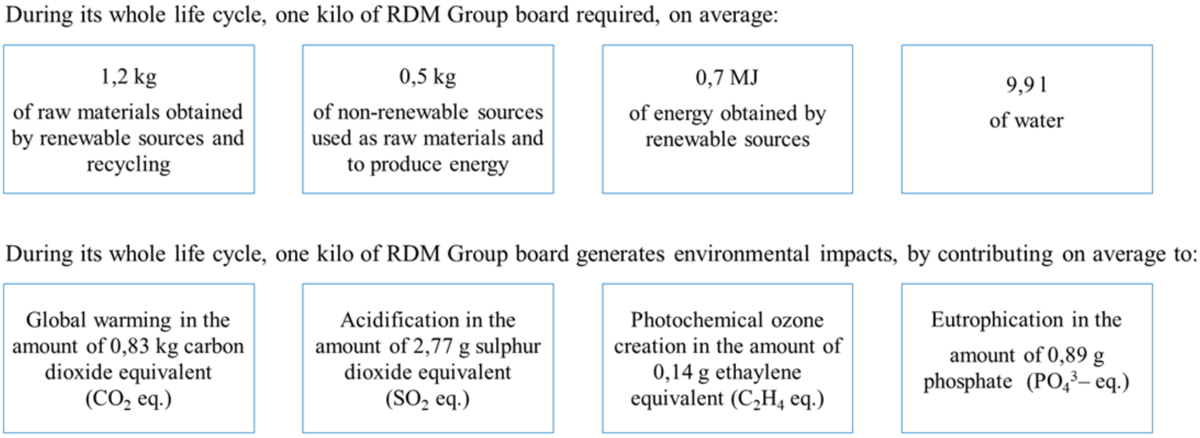
[89] http://economiacircolare.confindustria.it/ch/reno-de-medici-spa/

[90] There are sectors, such as the pharmaceutical or food ones, which for aesthetic reasons still require virgin fibre cardboard, that is a completely white cardboard, even the internal layers.

Moreover, the Group is involved in a dual industrial symbiosis. On the one hand, it uses secondary raw materials (processing scraps) and discarded or unsold goods (such as newspapers and magazines) from the industrial and commercial sector; on the other hand, it supplies its waste to other companies that use them as a production input. In fact, the fibres that are discarded by the paper mill, because of too low quality, are then reused in the production of cement or asphalt.

To continue improving the environmental compatibility of its products, RDM has conducted the Life Cycle Assessment on products manufactured in 2017. Through this method the Group measured in a systematic and thorough way the impact on the environment it generates through the production, use, and recycling of its board. These processes, indeed, require materials and energy, which generate burdens for the Planet, in the way of waste products and emissions in the atmosphere and water. The Figure 14 summarizes the results of the analysis[91].

Figure 14 – Reno De Medici cardboard Life Cycle Assessment



During its whole life cycle, one kilo of RDM Group board required, on average:

1,2 kg of raw materials obtained by renewable sources and recycling

0,5 kg of non-renewable sources used as raw materials and to produce energy

0,7 MJ of energy obtained by renewable sources

9,9 l of water

During its whole life cycle, one kilo of RDM Group board generates environmental impacts, by contributing on average to:

Global warming in the amount of 0,83 kg carbon dioxide equivalent (CO_2 eq.)

Acidification in the amount of 2,77 g sulphur dioxide equivalent (SO_2 eq.)

Photochemical ozone creation in the amount of 0,14 g ethaylene equivalent (C_2H_4 eq.)

Eutrophication in the amount of 0,89 g phosphate (PO_4^{3-} eq.)

Source: Reno De Medici's website

4.5.1 I4.0 technologies in Reno De Medici and their role in implementing CE principles

In giving new life to cellulose fibres, Reno De Medici applies technologies that improve the efficiency of production processes, maximize the use of resources, and minimize the amount of waste disposed in landfills.

An advanced technological equipment is used to monitor the qualitative data of the incoming waste paper. The instrument penetrates inside the waste bales to check, for example, the humidity or the presence of impurities. This allows to introduce cleaner secondary raw materials into the production process, reducing waste and resources consumption. Indeed, if a

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[91] http://rdmgroup.com/sustainability/ecodesign-of-the-product/

poor quality raw material was used, this would compromise the quality of the paper which would then be thrown away, and the resources used for its manufacture would be unnecessarily consumed.

Production planning is supported by a software in order to better manage it and avoid overproduction; artificial intelligence algorithms make forecasts on production levels needed to meet demand based on production data and customer present and past orders.

Within the production phases, Reno De Medici takes advantage of I4.0 technologies to monitor the processes; sensors in machineries collect a large amount of data about their functioning which are used to improve the production process's efficiency. Sensors allow machineries to diagnose a problem or failure autonomously and to communicate it to the operators, who therefore intervene promptly. In addition, thanks to the sensors, the consumptions of electrical and heat energy are constantly observed and analysed in order to minimize them. Moreover, computerized systems enable communication between machines by creating a seamless manufacturing process. All this makes it possible to optimize the production process, reducing the consumption of material, water, and energy. Thanks to Internet machines in production communicate with each other and exchange data with other company's functions. Real-time data about production levels are integrated with information about goods shipped and clients' orders to better manage raw materials supply and avoid overproduction.

RDM relies on I4.0 also to control product's quality. Any production defects, such as the presence of stains on the paper, are detected by an artificial intelligence, which elaborates images of the processing materials provided by cameras embedded in machines. If a defect is identified, the machinery cannot be stopped because in the paper mill equipment must work 24/7 to generate profit; any downtime would therefore be very expensive for the paper mill. As a consequence, the defective part is removed downstream, at the end of the production process, thanks to the cameras and sensors that during the manufacturing of the reel have precisely identified the portion containing the defect. In this way, a machine will cut only and exactly the defective part that will be discarded and returned to the production process as waste paper. These technologies allow RDM to minimize waste, discarding only the necessary, and prevent products from reaching the customer and then being sent back because they are defective, generating unnecessary transport and fuel consumption with related polluting emissions.

Furthermore, in the Italian plants RDM Group has invested in a technology capable of maximizing the amount of cellulose fibre extrapolated in the recovery paper processing process. The technology recovers the fibres still present in the pulper waste generated in the recycling process of the paper coming from urban separate waste collection. These fibres are then reintroduced into the production cycle, thus reducing processing waste and maximizing the use of raw material.

For what concerns logistics, in the French plant La Rochette, RDM has created a partially automated warehouse in which the reels ─ several tons of rolled cardboard ─ are automatically stored and picked up by an autonomous robot. Once the reels are finished, conveyor belts bring them to the warehouse; the robot takes the reels and stacks them in a perfectly aligned way at unreachable heights for traditional forklifts with grippers. The autonomous robot enables RDM to significantly increase the accuracy with which the goods are stored, avoiding potential damage to the goods, and consequent waste, which can instead be generated in the event that storing process is carried out by humans. The smart robot knows if the reel has to be stacked and then shipped or if it must be cut and sold in the form of pallets of cardboard sheets. In the latter case, the autonomous robot places the reel on another conveyor belt that takes it to a department where it is unrolled and cut into sheets. Finally, the cardboard sheets are stacked and the pallets thus created are brought on a conveyor belt to a robot which automatically creates the outer polyethylene coating. Taken together, these robots allow for more efficient logistics management and lesser error rate resulting in resource savings.

The Table 6 summarises the role of I4.0 technologies in implementing CE principles inside Reno De Medici.

Table 6 – I4.0 technologies in Reno De Medici and their role in implementing CE principles

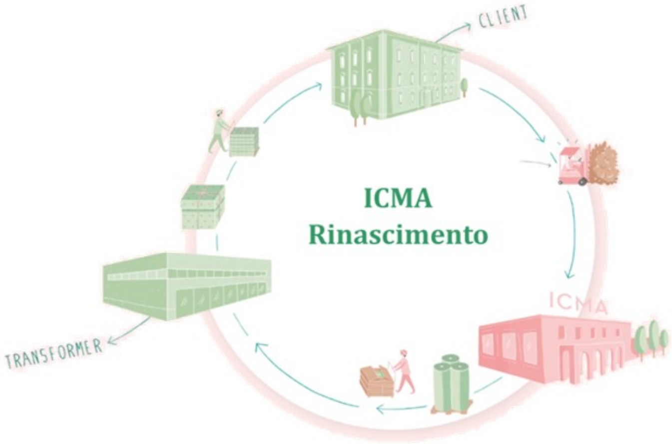
I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	Increase in logistics' efficiency and reduction in error rate and damages to goods enabled by automated warehouse.	Better maintenance decisions thanks to data provided by machines connected as a network.		
Internet of Things (IoT)	Real-time monitoring of material, energy, and water consumption, detecting inefficiencies.	Reduction in damages to machine' components through real-time data about machine allowing operators to intervene promptly in case of malfunctioning.		
Big data and analytics	Increase in efficiency of production process; optimisation of electrical and heat energy consumption.	Proper maintenance and repair of machine, lengthening its life cycle and favouring the reuse.		
Artificial intelligence (AI)	Precise identification of the reel's portion containing defects; elimination of unnecessary transports due to shipment of defective products; absence of overproduction through forecasts on production levels needed to meet demand.			
Autonomous robots	Reduction in error rate and damages to goods.			
Horizontal and vertical system integration	Elimination of wasteful duplication and redundant production; better raw material supply.			

Source: own elaboration

4.6 Icma S.r.l.

Icma Sartorial Paper is a Mandello del Lario (Lecco, Lombardy) company that since 1933 ennobles paper for luxury brands' packaging. It is a female-led company whose papers are a symbol of exclusivity, design, and all-Italian quality. The mission of Icma is to raise paper finishing to an art form and to turn sheets of paper into something unique, to manufacture in Italy, and enable its customers to experience the typical warmth, passion, and taste for beauty of Italian territory. To Icma, environmental sustainability is a modus operandi; since 2009 the company is FSC® certified and as of May 2020 it has become a B Corp. Its aim is to set a benchmark for customizable eco-friendly creative paper[92]. For this purpose, the company has created Icma 2030-Lab, a research program aimed at adopting good practices in terms of product and process sustainability. Within this program there is Rinascimento, a circular economy project with which Icma produces the paper for the customer's packaging using customer's own waste. Rinascimento represents the maximum expression of circular economy existing in the field of creative papers for luxury packaging. The Figure 15 depicts the process employed in Rinascimento.

Figure 15 – Rinascimento, Icma's circular economy project



Source: Icma's website

Cellulosic scraps generated by client (corrugated fibreboard boxes, cases, rigid boxes, shopping bags, displays, office paper, catalogues, magazines, etc.) are collected and taken to the paper mill where they are turned into 100% recycled and recyclable industrial paper. Then the paper is ennobled by Icma and transformed into creative paper for the specific orders from the client that had produced the initial scraps. Afterward the client' packaging supplier (the transformer in Figure 15) makes the packaging that go into the client's stores and which then

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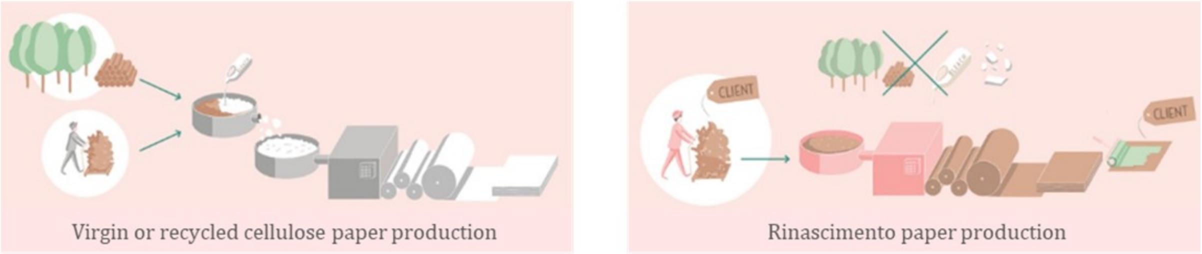
[92] http://www.icma.it/eng/

can be recycled again. The result of Rinascimento is that the paper returns to the user who will employ it in its boutiques giving it a new life, becoming a visible testimony of an innovative circular economy process. Throughout the whole supply chain, the scraps are traced to ensure that the waste produced by the customer is actually used to produce recycled paper for that client[93]. Icma handles all phases of the Rinascimento service, coordinating the stakeholders from the withdrawal of scraps at the company site to when they return to the client in the form of a new products.

The product obtained in Rinascimento project is FSC Recycled Credit certified and is in turn recyclable, thus preventing the production of waste. The yield of the raw material is maximized as the ratio between the paper produced and the waste paper used is approximately 1 to 1, much higher than the sector average which is around 0.7.

Rinascimento is a virtuous example of the reuse of materials; Icma manufactures new products directly from cellulosic scraps, eliminating the intermediate step ─ necessary for creative papers ─ of producing virgin or recycled cellulose pulp, a process that uses chemical products, energy, and water. In addition, the cellulose is neither bleached nor de-inked. Therefore, the production of creative papers with Rinascimento, shown in Figure 16, enables substantial savings in trees, chemicals, water, and energy. In addition, due to the shortening of the production process, material transportation is reduced, resulting in less CO_2 emissions. The careful planning of the service also contributes to this; Icma designs the supply chain choosing partners based on the geographical location of the scraps and the characteristics of the creative project[94].

Figure 16 – Differences between the traditional paper production process and Rinascimento process



Virgin or recycled cellulose paper production

Rinascimento paper production

Source: Icma's website

The company's goal is to replace all the papers it currently produces in partially recycled material or virgin fibre with material produced in the same way as in the Rinascimento project, so with a shorter production process and using 100% recycled paper.

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[93] http://economiacircolare.confindustria.it/ch/icma-srl/

[94] http://www.icma.it/eng/rinascimento/

Icma not only uses waste from other companies as a production input, but at the same time its scraps are reintroduced into the paper recycling circuit, becoming productive input for paper mills. In addition, some waste produced by Icma is reused by the company itself, decreasing resources consumption. The most important case is that of the reuse of the water used in the production cycle which is purified by means of a distiller.

Finally, the company pays attention to the environmental issue also with regard to energy; Icma, indeed, self-produces most of the electricity needs through photovoltaic panels installed on the roof of its factory.

4.6.1 I4.0 technologies in Icma and their role in implementing CE principles

Icma has invested in Industry 4.0 by implementing a wireless sensor network. The machines used in production are equipped with sensors and communicate with each other via wi-fi. The sensors make it possible to constantly monitor parameters such as speed, temperatures, and energy consumption; the data thus collected are then stored in a cloud. Icma relies on sensors in order to control machinery's status in real-time; in this way everything become transparent, including water and energy consumption during the production process of creative papers. This allows to improve the efficiency of the processes because excessive use of resources are identified and so optimized or eliminated. Equipped with sensors, machineries are able to signal any failure or malfunctioning in real-time thus giving the possibility to operators to intervene promptly. Consequently, components' breakage is avoided ─ which could occur if machine continues to operate despite the detection of a problem ─ thus extending their life cycle.

Again thanks to sensors in equipment, the quality of the product that the machine is manufacturing is monitored; if a defect is detected, the machine alerts the operator who immediately intervenes with the necessary corrective actions. The error has to be corrected not necessarily at the end of the production process, as happens in paper mills, but when it is detected, even by stopping the machinery if necessary, as a downtime has a much lower cost for a company that superficially transforms paper, like Icma, compared to the case of paper mills. The immediate identification of the defect and its correction allow Icma to avoid the production of further defective products which should then be discarded, generating material waste and making the consumption of energy and water, used for its processing, useless.

Furthermore, Icma has invested in state-of-the-art machineries to improve the filtering process ─ reducing the company's dust emissions ─ and the water purification process. In 2019, the company purchased a distiller having advanced technologies that allow it to purify the water used in the creative paper manufacturing process, which would otherwise be difficult to use, in a more efficient and less impactful way. The new equipment currently purifies about 70% of waste water, but once fully operational it will allow to purify 100% of this water, reducing Icma's waste of hydric resources to zero. Both the distillation and the filtration tools are equipped with interconnection systems in such a way that the control of commissioning and the correct functioning of these machines can be carried out from a single location or even remotely, instead to move around the factory. As happens in machines employed in production process, sensors embedded in these equipment enable to increase their efficiency; therefore Icma can generate the wider positive impact on the environment allowed by these new equipment in a more efficient manner.

Information exchange across the entire organization allows for the optimisation of the coordination between Icma's activities; the integration of data from the arrival of the raw materials to the shipment of finished products avoids an excessive supply of material and production.

Concerning the Rinascimento project, the company does not rely on I4.0 technologies, such as RFID, for the traceability of the customer's waste in order to ensure that this is actually used to produce new products for that specific client. To date, given the limited size of the project, the traceability of the material is possible simply by asking the waste paper management company to keep the waste of the customer involved in Rinascimento separate, labelling it so that it does not get confused with the rest of the production. Later, the paper obtained from this waste paper is treated separately by Icma throughout the production process to keep track of it. Icma states that in the future, if the Rinascimento project expands, more complex data management structures will certainly be needed. In this case, the RFID technology and the creation of a platform that integrates the data of the various companies involved in the project could be of great help in documenting the traceability of waste paper.

The Table 7 summarises the role of I4.0 technologies in implementing CE principles inside Icma.

Table 7 – I4.0 technologies in Icma and their role in implementing CE principles

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	Resource-efficient processes thanks to data provided by machines connected as a network.	Better maintenance decisions thanks to data provided by machines connected as a network.		
Internet of Things (IoT)	Real-time monitoring of material, energy, and water consumption, detecting inefficiencies.	Reduction in damages to machine' components through real-time data about machine allowing operators to intervene promptly in case of malfunctioning.		
Big data and analytics	Increase in efficiency of production process, and water purification and dust filtration processes.	Proper maintenance and repair of machine, lengthening its life cycle and favouring the reuse.		
Cloud computing	High degree of server utilization; lower energy consumption.	Storage of data used for improving maintenance decisions.		
Artificial intelligence (AI)	Elimination of unnecessary transports due to shipment of defective products; reduction of defective products manufactured.			
Horizontal and vertical system integration	Elimination of wasteful duplication and redundant production; better raw material supply.			

Source: own elaboration

4.7 TM Italia S.r.l.

TM Italia was founded in 1951 in the province of Ascoli Piceno, in the Marche region. It produces high-end furniture, mainly kitchens, rigorously made to measure. In TM Italia the made in Italy high craftsmanship meets innovation and technological research creating excellence[95].

The company has always adopted a systemic approach with respect to sustainability issues; TM Italia's circular economy approach embraces all business areas, from design, to procurement, from production to distribution, to use and disposal.

For what concerns design, every product is configured based on the needs of each individual customer, using only recycled and recyclable materials. In 2012 the company presented the Oreadi concept: a kitchen based on eco-design, with zero impact both in terms of production and in its actual domestic use. The Oreadi project integrated a water recirculation system, enabled by an intelligent sensor that analysed the waste water, purified it, and used it for the dishwasher and the internal garden; a natural refrigeration system ran without electricity; and even a plant air purification system based on special plants. Moreover, it had an internal vegetable garden, an internal composter, appliances only in class A +++, and it was made entirely of recycled and recyclable materials. Unfortunately, the Oreadi concept was not successful on the market as it was too innovative for a time when the environmental theme was not a hot topic as it is now[96].

Figure 17 – TM Italia's Oreadi concept

Source: TM Italia's website[97]

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[95] https://tmitalia.com/identity-the-culture-of-uniqueness/

[96] https://tmitalia.com/certifications-environment/

[97] https://www.tmitalia.it/wp-content/uploads/2014/11/20-10-12-ambiente-cucina.compressed.pdf

Regarding the procurement, each TM Italia product is a one-off. The company buys only the resources strictly necessary for completion of the orders acquired, generating zero waste. A logic in the opposite direction to the traditional practice of companies in the furniture sector, which stock supplies generating unsold and requiring logistics for a large amount of materials ─ not necessary in the one-off approach. In addition, the purchase process is based on a just-in-time approach that reduces the space used as a warehouse, along with the resources used for storage management.

The production, proudly 100% Italian, is made with FSC and PEFC[98] certified materials; all the panels are 100% made from post-consumer and recyclable wood certified Pannello Ecologico and Remade in Italy. In addition, all processing waste and dusts are collected and destined for recycling. Furthermore, the company self-produce 40% of the energy requirement through a photovoltaic system, resulting in a CO_2 savings of more than 40 thousand kg per year.

TM Italia pays attention to environmental issue also in the distribution phase. The company delivers the components strictly necessary for the installation of the product and there are no stock movements in the distribution chain for suppling retailers and/or wholesalers, eliminating the possibility of obsolescence of the goods and therefore waste. In addition, all loads are optimized through groupage, a technique that consists of putting together two or more shipments that have the same or near origin and destination in a single transport operation ─ or at least for a large stretch of the route[99]. Groupage avoids half-loaded trucks traveling with a consequent reduced environmental impact in terms of harmful emissions.

The commitment of the company to circularity theme extends also to use and disposal phases. The quality of the raw materials and the accuracy of the workings give birth to high quality furniture. This allows to increase the durability of the product thus extending its life cycle. TM Italia kitchens, indeed, have an average life span of over 20 years, well above the sector average. Furthermore, the way in which TM Italia furniture is created favours the reuse of materials used since all the components can be disassembled and recycled[100].

Thanks to the combination of all these elements, last year the company won the "Best Performer 2019-2020" award for the SMEs manufacturing category, as part of the

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[98] The Programme for the Endorsement of Forest Certification (PEFC) is a certification system for sustainable forest management.

[99] http://www.dizionariologistica.com/dirdizion/groupage.html

[100] http://economiacircolare.confindustria.it/ch/tm-italia-srl/

competition organized by Confindustria to reward the most virtuous Italian companies on the subject of circular economy.

4.7.1 I4.0 technologies in TM Italia and their role in implementing CE principles

In TM Italia, the production line integrates sophisticated woodworking techniques with advanced automation processes enabling the creation of an industrial structure although working on highly personalized and substantially unique projects. The company applies the latest technologies in order to optimize all its processes, from the product design to shipment, from a green perspective.

In the design phase, TM Italia relies on an advanced software that allows to see in the digital world each furniture before making it in the real world. This enables to test different shapes and compositions of product, finding the ones that best suit client without consuming the needed resources as it would be necessary in a real prototype. In addition, the software supports the design of the product indicating the combination of materials and elements that are possible and those that are not. There are some pieces of furniture that must necessarily be made with specific materials, others to which, for example due to their shape, stone cannot be applied, and so on. The digital tool allows the firm to avoid any mistake ─ for example that of ordering a material which then turns out not to be suitable for that type of furniture ─ thus allowing to reduce waste. The software has a very complex structure as it must be able to project into the digital world products to measure, unique in their characteristics; in fact, it incorporates about 150,000 codes, a number 100 times greater than that used by a company that works on standardized products. The development of this tool was a challenging project because, although the adoption of graphic configurators had been widespread for several years in the furniture sector, the company had a very wide product variability and so coding and digitizing this infinite variety has been extremely complicated.

Once the final design has been created, the software communicates directly to the machinery in production the cut that must be made to manufacture the components designed. Human error in this phase is completely eliminated and consequently also the relative waste of material generated. The machinery is able to distinguish different raw materials thanks to bar codes or QR codes that are applied to the raw material upon its arrival in the warehouse; they make it possible to uniquely identify the material during the entire production cycle, from when it enters the company to when it leaves it in the form of a final component. The codes are read by the optical devices of the cutting machines which, in this way, associate the cutting information provided by the management software to the material. The cutting machinery is a CNC[101] system equipped with artificial intelligence and an optical device thanks to which it analyses the surface of the material to be processed and cuts it in such a way as to maximize its yield. The smart equipment allows to optimize the resources use, decreasing production waste; the processing scraps from which the company can no longer obtain any shape are reduced to less than 10%.

Subsequently, the assembly of the elements is fully manual. Indeed, making low volumes and having customized products, therefore all different from each other, it is impossible to automate this process.

The packaging of each individual component is made to measure using recycled cardboard of the highest quality, which allows the reduction of transport damage and the absence of dimensional stocks. Even for the packaging, a CNC system, like the one used for cutting materials, is employed, making it possible to optimize the yield of cardboard sheets and minimise waste. This technology has been adopted for 3 years and it allowed the efficient creation of packaging to measure, that in turn has enabled to reduce product damage related to transport by more than 50%. The resulting environmental benefits are considerable. In fact, the damaged products were destined to landfill and the cycle to produce those components again had to be restarted.

The software that manages product design and cutting of materials also organizes outbound logistics, in particular the loading of goods into the truck for shipping. In the case of TM Italia, this process would be very difficult to manage manually; in fact a kitchen may consist of 1,000 different components that need to be shipped together. Each component is labelled with its own barcode or QR code; the software provides the warehouse worker with the codes of the materials that must be loaded on each truck. This makes possible a more efficient management of the warehouse, an improvement in logistics and the absence of errors, with a positive impact on the company, but also on the environment, deleting unnecessary movements of material and cutting on related CO_2 emissions due to shipment’s errors.

The handling of raw materials and components in the warehouse is automated; it takes place by means of mechanical arms, thus reducing the risk of accidents and damage to products.

Within the TM Italia factory, the machineries are connected to Internet and they are equipped with sensors gathering data and storing them in a server inside the company. Data collected about machineries’ functioning are used for monitoring and improving energy consumption and production efficiency with respect to objectives, or to daily/weekly yield, and for better planning maintenance.

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[101] A computer numerical control (CNC) is the automated control of machining tools by means of a computer.

Summing up, the software adopted by TM Italia allows to create an integrated system in which all steps required to create a new product and send it to the customer are connected and managed by this single tool. This allows to better coordinate the company’s activities, from inbound to outbound logistics, avoiding errors such as wasteful duplication of components or incorrect shipments. In the company, technologies have helped in the optimization of the design, the cutting process, the production of packaging, and the logistics, significantly reducing waste and the consumption of resources. All of these aspects allow the company to have a very low environmental impact.

The Table 8 summarises the role of I4.0 technologies in implementing CE principles inside TM Italia.

Table 8 – I4.0 technologies in TM Italia and their role in implementing CE principles

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	Resource-efficient processes thanks to data provided by machines connected as a network.	Better maintenance decisions thanks to data provided by machines connected as a network.		
Internet of Things (IoT)	Real-time monitoring of material and energy consumption, detecting inefficiencies.	Reduction in damages to machine' components through real-time data about machine allowing operators to intervene promptly in case of malfunctioning.		
Big data and analytics	Increase in efficiency of production process.	Proper maintenance and repair of machine, lengthening its life cycle and favouring the reuse.		
Simulation	No consumption of resources in the physical world for designing and testing products; absence of errors in product design.			
Artificial intelligence (AI)	Maximisation of the material yield.			
Horizontal and vertical system integration	Elimination of wasteful duplication and redundant production; elimination of additional transports due to wrong shipments.			

Source: own elaboration

4.8 Gusbi S.p.A.

Gusbi is a company located in Vigevano (Pavia, Lombardy) specialized in “turnkey” machineries for every kind of polyurethane unit soles and shoes. The firm mainly sells its equipment to shoe manufacturers abroad; today, over 1,000 Gusbi machineries are operational all over the world. The Gusbi brand means state-of-the-art machines, top quality moulds, qualified and continuous technical and commercial assistance, and constant development of new production techniques[102]. The company has been classified by Confindustria as one of the excellence of circular economy as it has managed to adapt one of its existing technology so that it could produce polyurethane soles using recycled material[103]. The technology was born to produce soles in polyurethane plus granulated cork for a particular customer. Gusbi’s innovation makes it possible to reduce to zero the waste of client companies. Any type of waste generated in the production of shoes ─ sole or upper parts ─, but even the entire product if defective, can be cut into granules and mixed with polyurethane for the production of new soles. In this way, no material is discarded, it is instead recycled, partly avoiding the need to consume new resources. Unfortunately, in order to ensure standards of resistance and flexibility of the sole, only a small percentage of recycled material, about 10-15%, can be used inside a sole; the waste, therefore, must be used only a little at a time.

Gusbi’s core business is the assembly of machinery made to order; 80-90% of the components are purchased externally and then assembled internally. This allows the company to minimize waste by ordering only the pieces necessary for the assembly of machinery requested by a specific customer. In addition, Gusbi reduces discarded materials by reusing the packaging from components ordered externally to pack machine elements or spare parts that the firm sends to its customers.

In recent months, there have been important developments in the footwear sector in terms of environmental sustainability. A supplier of Gusbi, a chemical company that produces polyurethane, has managed to create a type of polyurethane that derives exclusively from renewable sources and which could replace the traditional one, derived from oil. This material can be used in Gusbi machines without having to make major changes to them. Currently, the material is in the testing phase, but if the application to the production of soles were to be successful, this could revolutionize the sector from an environmental point of view.

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[102] https://www.gusbi.com/

[103] http://economiacircolare.confindustria.it/ch/gusbi/

4.8.1 I4.0 technologies in Gusbi and their role in implementing CE principles

The creation of the machinery for the production of polyurethane soles using recycled material did not come about as developments in the technologies applied by the company. The technology already existed and it has been exploited to shred the waste material of client footwear companies and mix it with polyurethane; the mixture thus obtained is then poured into the mould and cooked for a few minutes to create the sole. Therefore, I4.0 technologies do not play an important role in the material recycling process. However, these technologies, applied to the machinery produced by Gusbi, allow to achieve significant results in terms of circular economy by reducing waste and consumption of material, and extending the useful life of the equipment. The robots installed in the Gusbi machineries enabled to reduce by 90%, in some cases even 97%, the consumption of the substance that is sprayed on the mould to prevent the polyurethane from adhering to it. Indeed, in order not to make a mistake, the operator used 3 grams, or even 10 grams, that are more than the necessary material, generating waste; on the contrary, the robot is able to dispense exactly the indispensable amount, namely 0,3 grams.

Gusbi machineries are connected to Internet; the connection allows Gusbi to remotely monitor the machinery's operation and provide assistance to customers who request it. Since the machines are located all over the world, remote assistance allows Gusbi to provide customer support at a very low cost compared to sending a technician on site and, at the same time, generates a positive impact on the environment ─ because, as said for Lucart, it avoids travels and related consumption of resources and fuel usage. The data collected on the customers' machineries are stored on a cloud. Through Internet, Gusbi is able to access information on the functioning of the customer's equipment and to support it in solving any problem and in correct maintenance. The sensors embedded in the Gusbi machinery allow to identify exactly what the problem is; for example, they can indicate precisely which is the faulty component that needs to be repaired or replaced. This enables the machinery to be repaired in the best possible way by extending the life cycle of the product. In fact, if subjected to proper maintenance and repair in case of breakdown, Gusbi machinery can last from 40 to 50 years allowing to keep resources in use for a long time. Moreover, the durability of the product favours the reuse of the machinery through the second- and third-hand market. Sometimes, clients return the machinery to Gusbi, which remanufacture and sell it again; retrofitting is usually required because electronical components of the machinery become obsolete. In addition, retrofitting is needed to equip old machinery with the latest I4.0 technologies.

Through the Internet, the client company's office that deals with orders management can communicate information on the sole to be produced (shape, colour, and quantity) directly to its Gusbi machinery in production. The robot employed in the Gusbi machine is equipped with an RFID reader that allows it to recognize the sole mould thanks to the tag inserted in it. Once the mould is recognized, the robot associates to it the information it had received from the orders office and begins processing. The robot, in turn, transmits to the office real-time data on the quantity of products manufactured. The RFID technology enables the machine to know exactly the type of processing it has to carry out and the quantity of products it has to produce to complete the order; as a consequence, production errors and related discarded goods are reduced to zero.

Moreover, Gusbi relies on simulation for machinery design and testing. A 3D software is used to develop machinery basing on the layout of the client's plant and to create a "digital twin" of the of the actual machinery to be built. The digital twin allows to simulate equipment movements in order to test if there could be some collisions between the different components. This is a crucial phase for the company as a millimetre can determine the non-operation of the machinery, with consequent large economic damages for the company. The digital twin enables Gusbi to test a machinery before manufacturing it in the physical world, resulting in a great advantage for the firm: it avoids the company to bear the huge expenses necessary to build and test the machinery in reality. The environmental impact of this solution is significant, since it eliminates the consumption of materials and waste generated in the testing phase.

Furthermore, in Gusbi, resource saving is also supported by additive manufacturing. A 3D printer is applied for manufacturing components' prototypes. The firm creates 3D file of components which then are printed by an external partner company. If the test of the plastic component gives a positive result, then the final aluminium component is made. As in the case of simulation, additive manufacturing allows the company to reduce costs ─ as a plastic prototype is less expensive than a metal one ─ and the consumption of resources. In fact, in the past the creation of the prototype took place in the milling department, where an operator made the piece starting from the metal block and subtracting material that was then discarded. On the contrary, the 3D printer, exploiting an additive process, allows to use only the material necessary for the creation of the component. Moreover, 3D printing partly favours recycling as the plastic material used in printer can be easily recycled by melting it, with a minimum loss of material.

In Gusbi, data are exchanged between different firm's functions; machine's elements manufactured internally are produced through CNC machines which communicate in real-time the number of components made to the sales department. This allows to better manage orders and avoid overproduction of components, and so waste. In addition, thanks to IoT, the company has access to machines' data of clients that have given the consent. This form of vertical system integration is used by Gusbi to provide a service to customers which can see their machine's data on a webpage, easily monitor their process detecting inefficiencies, and receive maintenance advices by Gusbi. However, these data are not used by Gusbi to provide clients with additional services, such as anonymous comparison between firms' performances to identify resource consumption patterns and establish if opportunities for improvements exist. Indeed, all Gusbi machines are highly customised and carry out different operations based on the needs of each specific client, rending comparison impossible. Nevertheless, thanks to data collected on client's machines, Gusbi can know exactly the conditions of equipment sold and its history (past breakdowns, malfunctions, and so on); these data facilitate Gusbi in remanufacturing process in the cases in which customers return machines to Gusbi that sell them in the second-hand market.

The Table 9 summarises the role of I4.0 technologies in implementing CE principles inside Gusbi.

Table 9 – I4.0 technologies in Gusbi and their role in implementing CE principles

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	Resource-efficient processes thanks to data provided by machines connected as a network.	Better maintenance decisions thanks to data provided by machines connected as a network.		
Internet of Things (IoT)	Real-time monitoring of material and energy consumption by Gusbi machines, detecting inefficiencies; elimination of technicians' travel through remote assistance.	Reduction in damages to Gusbi machine' components through real-time data about Gusbi machine allowing operators to intervene promptly in case of malfunctioning.		
Big data and analytics	Increase in Gusbi machine's efficiency.	Proper maintenance and repair of machine, lengthening its life cycle and favouring the reuse.		
Cloud computing	High degree of server utilization; lower energy consumption.	Storage of data used for improving maintenance decisions.		
Additive manufacturing (AM)	Creation of prototypes using exactly the amount of material required, without waste.		Easy recycling of plastic material with minimal loss of material.	
Simulation	No consumption of resources in the physical world for designing and testing products.			
Autonomous robots	90-97% reduction in material consumption to coat the mould; absence of production errors thanks to RFID technologies embedded in Gusbi machines.			
Horizontal and vertical system integration	Elimination of wasteful duplication and redundant production of components; better raw material supply.	Easier remanufacturing process.		

Source: own elaboration

4.9 Results of the analysis

From the analysis of the Italian companies interviewed, it emerges that I4.0 technologies contribute in reaching circular economy objectives. Indeed, intervening on the efficiency of production processes, on product design, on the management and control of raw materials, and on the outbound logistics, I4.0 technologies help companies to meet the CE principles. However, I4.0 technologies do not always directly support the implementation of the specific circular projects that companies promote and for which they have been classified as "Excellences in the CE" by Confindustria ─ such as Natural in Lucart or Rinascimento in Icma. These projects, instead, exploit less advanced technologies. In Natural, the separation of the tetra pak into its components occurs through a physical process; in Rinascimento, the management and traceability of the waste paper takes place with traditional methods such as reserving parts of the warehouse for the waste paper of the specific customer and coordinating with actors involved in the project through direct communication between workers, without relying on advanced digital platforms. Moreover, the recycling project of the coated cardboard supported by Reno De Medici leverages on chemical-physical processes that do not use cutting-edge technologies. Furthermore, Gusbi machinery that allows to produce polyurethane soles using recycled material is not enabled by highly advanced technologies; it exploits an existing technology that simply shred material destined to be discarded and mix it with new polyurethane. TM Italia is the only case in which the specific circular economy project, the Oreadi concept, is directly supported by I4.0 technologies; in fact, it is only thanks to the presence of intelligent sensors that the kitchen is able to recycle waste water. Therefore, I4.0 technologies have a less important role in carrying out the particular initiatives promoted by companies on the CE theme, but they provide a great support in implementing the fundamental principles of circular economy.

In particular, in the companies analysed, the I4.0 technologies contribute mainly to the Reduce and "Design out of waste and pollution" principles. IoT, together with big data and analytics, represents the major enabler of these principles. IoT makes it possible to largely increase production processes' efficiency reducing the amount of resources ─ such as raw materials, water, and energy ─ consumed; in fact, it enables companies to observe processes and monitor equipment's function in real-time, identifying any inefficiencies in resources use and allowing to correct them. Decreasing resource consumption is very important mainly in the paper industry, which is characterised by an intensive use of energy and water. In some companies, such as in Icma, IoT helps also in optimising water's distillation and dusts' filtration processes, allowing to reuse water resources and reduce emissions efficiently. In addition, in Lucart and Gusbi, IoT supports pollution's reduction through remote assistance which avoids technicians' travels and related CO_2 emissions. All the companies interviewed collect a huge amount of data thanks to sensors embedded in their equipment; in some cases data are stored on a cloud, namely in Lucart, Icma, and Gusbi, while in the others on internal servers. The use of cloud data centers allows to lower energy consumption, and therefore CO_2 emissions, and to maximise server utilization. Data are leveraged by companies to assess and optimise the use of resources in the various stages of production processes.

Resource savings are also enable by CPSs; in Lucart and Reno De Medici, automated warehouses allow for more efficient logistics management and minimization of storage and shipping errors. Additionally, resources' usage is maximized as automated warehouse makes the most of the space available in the factory and, in the case of Lucart, organize shipments so that the trucks always travels at their maximum load capacity. In CPSs machines and devices are connected as a network and exchange data which are leveraged for optimising resource usage and thus reaching resource-efficient processes.

Moreover, the fulfilment of the Reduce principle is supported by simulation that is leveraged in TM Italia and Gusbi to design and test products without consuming physical resources.

For what concerns waste reduction, a great contribution is given by the adoption of autonomous robots which lower the error rate and damages to goods resulting in discarded material or use of additional resources for rework. Furthermore, in Lucart, Reno De Medici, and Icma, machines are equipped with optical devices or sensors collecting data on the characteristics of the products they are manufacturing; images and information are elaborated by an artificial intelligence which is able to detect quality defects and signal them promptly to operators, avoiding the production of further defected products resulting in waste. In addition, in TM Italia, it is possible to see another application of the artificial intelligence resulting in waste reduction; AI analyses raw material's surface and decides how to cut it in order to maximize its yield.

Moreover, in Gusbi, resource savings and waste reduction are achieved through additive manufacturing that allows to use exactly the material necessary for the creation of the component prototype, without waste.

In the companies analysed, the horizontal system integration allows to optimize the coordination between different firm's activities, increasing processes' efficiency and reducing waste. For instance, in TM Italia, the device used to design the product communicates directly to the cutting machinery which cuts materials exactly according to information received, without possibility of error and therefore discarded materials. In addition, data exchange across the entire organization enables to better organise raw materials supply and productions levels, thus avoiding excessive stocks of resources and overproduction. As an example, in Lucart, a worker in Diecimo plant knows exactly the amount of products present in that production plant and in the logistic hub thanks to the integration of data about the two site; in this way, wasteful duplication or redundant production are eliminated.

I4.0 technologies help companies also in meeting the Reuse and "Keep products and materials in use" principles, although to a lesser extent than they do for the principles just discussed. In the interviewed firms, the main contribution to these principles is given by CPSs, IoT, big data and analytics, and cloud computing. Through sensors and actuators machineries become "smart"; they know their location and condition collecting real-time data about themselves which are stored on clouds or internal servers. A smart equipment is able to flag any functioning problem enabling operators to intervene promptly and avoid components' breakage, thus extending their usage life. In addition, the huge amount of data gathered about machine allows a proper maintenance and repair, lengthening its life cycle and favouring the reuse through the second-hand market.

Simulation provides little help in the fulfilment of Reuse and "Keep products and materials in use" principles; in Lucart, a software supports technicians in assessing the environmental impact of products, however, most of the work is still done by humans. In none of the companies analysed there are advanced systems that simulate the composition of the product and autonomously suggest the one that allows the longest life cycle through reuse.

Also vertical system integration partly contributes to these principles; in Gusbi, data collected on clients' machines facilitate the remanufacturing process for the mechanical company.

In the companies interviewed, additive manufacturing, artificial intelligence, and autonomous robots give no contribution to Reuse and "Keep products and materials in use" principles.

In the interviewed firms, additive manufacturing is the only technology favouring Recycle; indeed, 3D printers use substances easy to be recycled, with a minimum loss of material. The other I4.0 technologies do not support the fulfilment of the Recycle principle. The main explanation is related to the sectors analysed. In the paper and furniture industries, the process of separating the product into its components, necessary for recycling, takes place through physical processes. Companies do not used advanced technologies, like autonomous robots provided with AI capable of recognizing the different materials and separating them, as proposed in the literature. In addition, products manufactured in these sectors are not equipped with chips and sensors which, at the end of the product's useful life, give information about materials embedded into components, easing the disassembly and recycling processes. Technologies like these are easier to find in industries such as that of electronics or household appliances. As regards the mechanical sector, recycling mainly concerns the metals used in machineries. The analysed company, belonging to this sector, does not rely on Industry 4.0 technologies in order to facilitate the recycling of the metals it uses in the construction of its machineries.

In the literature, IoT, big data and analytics, additive manufacturing, and AI are identified as enabler I4.0 technologies of "Regenerate natural systems" principle. However, the companies interviewed do not yet exploit these technologies for this purpose. For example, the data collected by the photovoltaic systems adopted by firms are not combined with weather data ─ as occurs in the most advanced existing systems ─ allowing the renewable plants to operate at their maximum potential. At the same time, AI is not used, for instance, for designing new materials which may substitute harmful chemicals currently used. Moreover, 3D printers adopted by Gusbi do not employ materials based on renewable sources contributing to "Regenerate natural system".

The companies belonging to the interviewed sample do not adopt augmented reality; consequently, in this section, this technology was not considered when discussing the role of I4.0 technologies in implementing CE practices.

The Table 10 summarises the contribution of the I4.0 technologies to the implementation of the CE principles in the Italian companies interviewed. The table has the same structure applied in the Table 2 (Chapter 2): the full dots represent the level of intensity with which the technology supports the analysed firms in meeting CE principles. Three dots indicates that the technology gives a large contribution in the fulfilment of the CE principle; two dots stand for a lower contribution, and one dot means that the technology offers little support in implementing the CE principle. Zero dots indicate that the technology does not represent an enabler for the CE principle in the companies analysed.
To facilitate the comparison with the results arisen from the literature (Table 2), the clear dots present in Table 2 are represented in Table 10 in the cases in which the level of the contribution of the I4.0 technology to the CE principle is greater in the literature than in the empirical research; instead, in cases where the contribution is the same the dots coincide and

only full dots are represented. There are no cases in which the contribution emerged in literature is lower than that found in the empirical research.

Table 10 – The role of I4.0 technologies in implementing CE principles in the Italian companies interviewed

I4.0 technologies	CE principles			
	Reduce & Design out waste and pollution	Reuse & Keep products and materials in use	Recycle	Regenerate natural systems
Cyber-Physical systems (CPSs)	●●●	●●	○	
Internet of Things (IoT)	●●●	●●○	○	○
Big data and analytics	●●●	●●○	○○	○○
Cloud computing	●●	●	○	
Additive manufacturing (AM)	●●●	○○	●○○	○○
Simulation	●●○	●○○		
Augmented reality (AR)	○○○	○○		
Artificial intelligence (AI)	●●●	○○	○○	○○
Autonomous robots	●●○	○○	○○	
Horizontal and vertical system integration	●●	●○	○○	

Source: own elaboration

From the Table 10 it is possible to see that, in the companies analysed, the I4.0 technologies contribute mainly to the Reduce and "Design out of waste and pollution" principles and, to a lesser extent, to the Reuse and "Keep products and materials in use" principles. In addition, they only partially support Recycle, while they do not contribute to "Regenerate natural systems".

Comparing the results arisen from the empirical analysis with those found in literature, it emerges that in the companies interviewed the contribution of I4.0 technologies to the fulfilment of CE principles is lower than that described in the literature. This is partly due to the fact that the analysed companies do not exploit the I4.0 technologies to their maximum potential, using them in all the ways proposed in literature. In fact, this would require huge investments that the Italian companies interviewed are not yet ready to make. At the same time, the lower contribution of I4.0 technologies to CE is partly due to the sectors chosen for the analysis, in which some I4.0 technologies' applications are unlikely to be implemented. For example, in the paper industry, it is difficult to find smart products equipped with sensors in order to be tracked throughout their life cycle. This solution can be very useful for monitoring the location of valuable materials, like rare metals, or very harmful ones, to favour their recovery and reuse or correct disposal, but it is of little use in the case of cardboard where the product can be recovered simply through the urban collection or waste management companies, which bring the material to the paper mills. Moreover, the company would not have the convenience to do so as the sensor could cost more than the product itself.

To summarize, in the Italian companies interviewed, I4.0 technologies support only partially the circular economy in terms of recycling, and although they do not support the use of renewable energy and materials, they make a great contribution in reducing waste and material and energy consumption, while curtailing CO_2 emissions too. In addition, they help in maximizing resources used and extending the life cycle of machineries. These results, combined with the environmental benefits generated through the circular economy projects promoted by the companies, allow them to operate in a responsible manner, helping to save the Planet.

CONCLUSIONS

The aim of this study was to investigate the role of Industry 4.0 technologies in implementing the principles of Circular Economy in manufacturing companies. While there is an extensive literature on the topics of Industry 4.0 and Circular Economy, few studies deal with the relationship between the two. Consequently, the intent was to contribute to the integration of these increasingly popular themes.

Circular economy is governed by the 3R Principles ─ Reduce, Reuse, and Recycle ─ which can be integrated by the three principles developed by the Ellen MacArthur Foundation ─ namely “Design out waste and pollution”, “Keep products and materials in use”, and “Regenerate natural systems”. As they are partly overlapping, in dealing with the potential contribution of I4.0 technologies to the CE, some of these principles were discussed together. In particular, the CE principles were grouped in four macro-principles: Reduce and “Design out waste and pollution”, Reuse and “Keep products and materials in use”, Recycle, and “Regenerate natural systems”. The available literature has been analysed in order to investigate how the main I4.0 technologies can support manufacturing companies in meeting each of the macro-principles. Specifically, were examined the Cyber-Physical Systems (CPSs), Internet of Things (IoT), big data and analytics, cloud computing, as well as additive manufacturing, simulation, augmented reality, artificial intelligence, autonomous robots, and horizontal and vertical system integration. From the literature analysis, it emerged that I4.0 technologies can greatly contribute to the fulfilment of CE principles, in particular to the Reduce and “Design out waste and pollution”, and Reuse and “Keep products and materials in use”. The employment of I4.0 technologies, indeed, allows companies to increase the efficiency of materials and energy use, reduce waste generation, maximise resource usage, extend products life cycle, as well as simplifies recycle procedures, and favours the use of renewable resources.

Companies can obtain many benefits from integrating the Circular Economy and Industry 4.0. Indeed, a smart green factory can enjoy the advantages arising from both the implementation of CE practices, and the application of I4.0 technologies; at the same time, as seen above, I4.0 technologies support firms in achieving CE objectives and thus in obtaining related benefits. The adoption of I4.0 technologies brings companies several benefits such as increased productivity, enhanced assets efficiency, quality improvement, match of supply and demand, and reduced time to market. Moreover, by shifting their operations in line with CE principles, companies can enjoy additional benefits like cost savings, increased revenues, reduced volatility and greater security of supply, high innovativeness, improved corporate reputation, and brand repositioning.

Real cases of companies practicing the circular economy have been analysed in order to investigate whether, and if so how, the I4.0 technologies help them in meeting the circular economy objectives. The aim was to verify the results that had emerged from the literature analysis. For the study, some Italian manufacturing companies classified by Confindustria as "Excellence in the circular economy" have been interviewed. The companies belong to some of the typical sectors of Made in Italy, specifically paper, furniture, and mechanical industries. From the analysis, it emerged that I4.0 technologies help the interviewed firms to meet CE principles by intervening in different parts of the firms' value chain, from inbound logistics, to production, to outbound logistics. I4.0 technologies, instead, have a less important role in implementing the specific circular economy projects promoted by the companies; these projects, indeed, rely on less advanced technologies. In particular, in the companies analysed, the I4.0 technologies strongly contribute to the Reduce and "Design out waste and pollution" principles; a lower contribution is given to Reuse and "Keep products and materials in use" principles, while they support only partially the Recycle principle. Finally, I4.0 technologies do not support "Regenerate natural systems" principle.

From the comparison between the results of the empirical research and those arisen from the literature analysis, it emerged that in the firms interviewed the contribution of I4.0 technologies to the fulfilment of CE principles is lower than that described in the literature. This is partly due to the fact that the Italian companies interviewed do not leverage I4.0 technologies to their maximum potential, and partly to the industries chosen, in which some applications of I4.0 technologies are difficult to implement. Additional researches on Italian companies operating in different sectors are recommended in order to further investigate the role of Industry 4.0 technologies in implementing circular economy practices.

APPENDIX: GUIDELINES FOR THE INTERVIEW

Qualitative Analysis
Circular Economy and Industry 4.0

Circular Economy

1. What does being circular mean for your company?
2. Your being circular is mainly based on *(many answers as possible)*:
   - ☐ Reduction in resource use (raw materials, water, energy)
   - ☐ Prevention of waste production
   - ☐ Reduction of waste
   - ☐ Reduction of harmful emissions
   - ☐ Reuse/recycling of waste from own activities within own production cycle *(with respect to the waste from the production process, specify what is reused/recycled)*
   - ☐ Reuse/recycling of waste from own activities by other companies *(with respect to the waste from the production process, specify what is reused/recycled)*
   - ☐ Use of scrap materials from other firms
   - ☐ Use of renewable raw materials
   - ☐ Use of electrical/thermal energy from renewable sources
   - ☐ Extension of the products life cycle by increasing their durability
   - ☐ Extension of the products life cycle by increasing the possibility of being repaired or reused
   - ☐ Other *(specify)*
3. What circular economy project has been undertaken by your company?

Industry 4.0

4. Which Industry 4.0 technologies have been adopted by your company?
   - ☐ Cyber-Physical systems (set of physical and cyber elements that interact with the surrounding environment, collaborate with humans, collect data, and, through feedback, adapt to new conditions in real-time (e.g. automated guided vehicles, robots that collaborate with humans, automated warehouses, etc.))
   - ☐ Internet of Things/smart products (machines/products connected to Internet and to each other through RFID, sensors, etc.)
   - ☐ Big data (data collection and processing systems)
   - ☐ Cloud computing
   - ☐ Additive manufacturing (e.g. 3D printers)
   - ☐ Simulation (e.g. software to test production processes or products design)
   - ☐ Augmented reality
   - ☐ Artificial intelligence
   - ☐ Autonomous robots
   - ☐ Information systems capable to exchange information with suppliers/customers or across the entire organisation, from inbound logistics, through production, marketing and sales, to outbound logistics
5. In your opinion, which of these technologies have supported your company in implementing the activities referred to in point 2? How?

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