MÁSTER UNIVERSITARIO EN

INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

A REVIEW OF INDUSTRY 4.0 POTENTIAL TO ACCELERATE THE TRANSITION TO A CIRCULAR ECONOMY

Estudiante *Irache Cabello Iñigo*
Director/Directora *Minguez Gabiña Rikardo*
Departamento *Expresión Gráfica y Proyectos de Ingeniería*
Curso académico *2019/2020*

Bilbao, 31, Agosto, 2020

ABSTRACT

The actual model of consumption is challenging the planet capabilities to withstand the pressure generated from excess resource consumption. The continuous growth of population and the increment of the middle class threats planet's sustainability. The model of Circular Economy based on the optimization of resources trough the maximization of use and the reduction of waste, appears as the new key to solve the problem. However, the transition to this new system comprises a certain degree of complexity. At same time, industry is confronting its fourth revolution also known as Industry 4.0, which intends to digitalize the whole industry through the use of technologies like the Internet of Things or Additive Manufacturing with the aim of optimizing the industrial systems. Along this work both terms of Circular Economy and Industry 4.0 are presented and analyzed in order to generate an adequate context for providing an insight of how these emergent industrial technologies can accelerate the transition to this new model of economy. This work has the intention of serving as foundation for future research around a topic that offers a great potential and still remains underdeveloped.

Key words: Sustainability, Circular Economy, Industry 4.0, Internet of Things, Additive Manufacturing, Transition.

RESUMEN

El modelo actual de consumo desafía las capacidades del planeta para soportar la presión generada por el excesivo consumo de recursos. El crecimiento continuo de la población y el incremento de la clase media en el mundo amenaza la sostenibilidad. El modelo de Economía Circular basado en la optimización de los recursos a través de la maximización de su uso y la reducción de residuos, aparece como la clave para solventar el problema. Sin embargo la transición hacia este nuevo sistema comprende cierto grado de complejidad. Al mismo tiempo la industria enfronta su cuarta revolución, también conocida como Industria 4.0, que propone digitalizar el total de la industria a través de tecnologías como el Internet de las cosas o la impresión 3D con el objeto de optimizar los sistemas industriales. En este trabajo se presentan ambos conceptos de Economía Circular e Industria 4.0 con el objeto de generar un contexto adecuado sobre el cual analizar cómo estas emergentes tecnologías industriales pueden ayudar a acelerar la transición hacia el nuevo modelo de economía. Con la intención de que este trabajo sirva como una buena base sobre la cual desarrollar futuras investigaciones alrededor de un tema que posee gran potencial y aun no se encuentra suficientemente desarrollado.

Palabras clave: Sostenibilidad, Economía Circular, Industria 4.0, Internet de las cosas, Impresión 3D, Transición.

LABURPENA

Egungo kontsumo-ereduak erronka egiten die planetak baliabideen gehiegizko kontsumoak eragindako presioa jasateko dituen gaitasunei. Biztanleriaren etengabeko hazkundeak eta munduko klase ertainaren hazkundeak jasangarritasuna mehatxatzen du. Ekonomia zirkularraren eredua baliabideen optimizazioan oinarritzen da, erabilera maximizatuz eta hondakinak murriztuz, eta arazoa konpontzeko gakoa da. Hala ere, sistema berri horretaranzko trantsizioak konplexutasun maila bat hartzen du. Aldi berean, industriak aurre egiten dio bere laugarren iraultzari, Industria 4.0 izenaz ere ezagutzen dena, industriaren guztizkoa digitalizatzea proposatzen duena, Gauzen Internet edo 3D inprimaketa bezalako teknologien bidez, industria-sistemak optimizatzeko asmoz. Lan honetan, Ekonomia Zirkularra eta Industria 4.0 kontzeptuak aurkezten dira, testuinguru egoki bat sortzeko helburuarekin. Testuinguru horretan, industria-teknologia berri horiek ekonomia-eredu berrirako trantsizioa bizkortzen nola lagun dezaketen aztertzen da. Lan hau potentzial handia duen eta oraindik behar bezala garatuta ez dagoen gai baten inguruko etorkizuneko ikerketak garatzeko oinarri ona izan dadin.

Hitz-gakoak: Iraunkortasun, Economia Zircular, Industria 4.0, Interneten gauzak, 3D inprimatzaile, trantsizio

Table of Contents

List of figures

List of tables

Abbreviations

"AM"-Additive Manufacturing

"AR"-Augmented Reality

"BDA"-BigData Analytics

"CO_2"-Carbon dioxide

"CAD"- Computer-Aided Design

"CE"-Circular economy

"DT"-Digital Twin

"EEA"-European Environment Agency

"Eol"-End of life

"EU"-European Union

"GDP"-Gross domestic product

"GHG"- Greenhouse gas

"IT"-Information technology

"IoT"-Internet of things

"PLM"- Product lifecycle management.

"SDG"-Sustainable development goals

"SME"- Small and medium sized enterprises

"PLC"- Programmable Logic Controller

"RFID"- Radio-frequency identification

"4IR"-Fourth Industrial Revolution

Introduction

Humanity has been facing challenges of all kind during its development through the years, in the last decades the concern about the planet capability of providing enough resources and stand human disruption has emerged as the main barrier for pursuing development. The evolution of modern society has been accompanied with an increase in the consumption of resources along with an increment in environmental damage.

There are many convincing facts that suggest that this model of production-consumption is becoming obsolete with regards of meeting the sustainable challenges that human society faces. What served in the past is no longer capable of creating opportunities for the future. The traditional linear economy, where the resources are taken for granted and the waste is hide behind the carpet needs to come to an end.

Decupling economic growth from resource consumption is a must for achieving sustainable goals. Here is when the concept of Circular Economy arises as an opportunity for change to a more sustainable paradigm, a system that is based on the optimization of the potential of resources by generating value through maximizing the use, minimizing the waste and desmaterilazing when possible. The reasons for implementing a circular approach to the production system are becoming more appealing as the linear system drawbacks are being put in evidence. The actual way of producing goods generates an estate of excessive pressure on the ecosystems out of which environmental risks arise; these risks endanger the provision of essential ecosystem services, such as water, air and soil cleaning [2].

However the implementation of a Circular Economy is still far from being fully accomplished, new strategies and innovations are required in order to achieve this new system. In this context the so called fourth industrial revolution which aims to bring the last developments of digital applications to the industrial sector, despite not being intended for that purpose appears as potential tool for accelerating the transition to CE.

Through this work both topics of Circular Economy and Industry 4.0 are presented and analyzed from various perspectives, in order to provide valuable insights for the reader. The topic of CE is introduced to the reader regarding its main principles, implications and the actions required for implement it. Then Industry 4.0 is characterized from the main features that introduce, the analysis of the key technologies that includes and the challenges its present for its implementation.

Finally an analysis of how the 4IR technologies can enhance the transition to CE is provided from both a theoretical and practical perspective. The first analyze the main findings of the existing literature regarding this topic and the latter presents a series of particular case studies that exemplifies some of the ideas theoretically presented.

Context

The desire of developed countries of acquiring permanent states of well-being through linear economy systems, where final products are the priority and resources are just vehicles, has led to a situation where the system is no longer able to fulfill the society demands without compromising the planet integrity. And the future outlook is even more discouraging as every week, the global population grows by 1.5 million people, 3 million people enter the middle class and 3 million people moves from a rural to an urban area [1].

Natural resource consumption

Human activities in particular the actual model of consumption is challenging the capacities of natural ecosystems by trespassing the planetary boundaries where the planet safely operates Figure 1, natural resource consumption is considered to be one of the main challenges for sustainable development as resource extraction and processing cause 90% of global biodiversity loss and water stress, and more than half of the impacts related with climate change [2]. The increase in population and the raise in resource consumption from developing countries has led to a yearly growth in material resource consumption; this growth poses a threat to sustainability at a local and global level, in fact the actual linear model of consumption has led to the use of 92 billion of tons of resources in 2017 a number that triples the value of 1970 and without action is expected to rise to more than 190 billion by the year 2060, pushing the boundaries where planet safely operates and endangering human life on earth [2].

Furthermore, resources are unevenly distributed around the world, which affect its prices and generate conflicts for getting access to them [3]. Poverty and social inequalities are a result of a system where the developing countries provide the labor workforce to address the needs of rich countries.

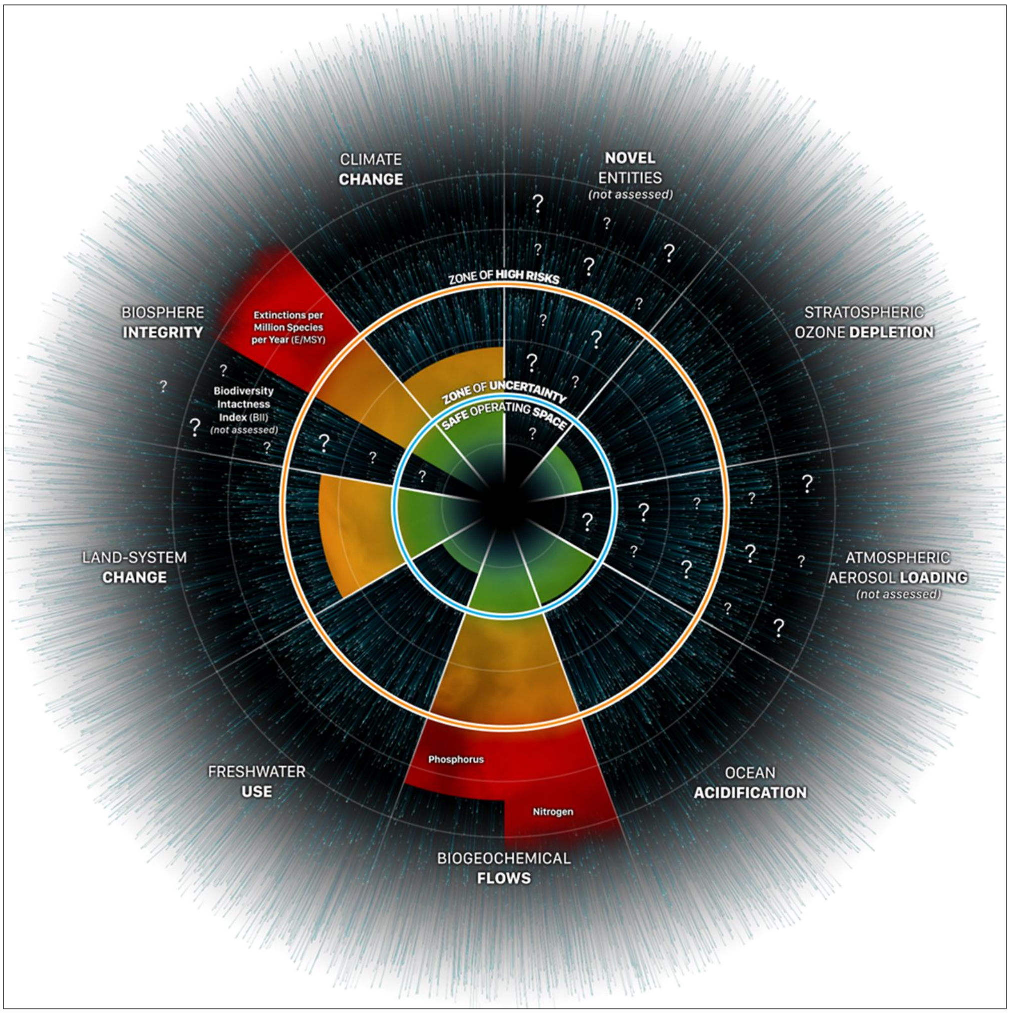

Figure 1: Current planet boundaries [4]

Sustainability and Circular Economy

In dealing with the environmental, economic and social challenges that the linear economy generates the concept of Sustainability appears as the keystone for change. A simple but straight definition of the concept was given by 1987 report of the *World Commission on Environment and Development* "Meeting the needs of the present without compromising the ability of future generations to meet their own needs."

Sustainability is based on three pillars that sustain the essence of the concept:

- *Environmental*. Meeting the needs without exhausting our natural resources and avoiding damage to natural ecosystems.
- *Social.* Meeting the needs with long term social well-being and reduced societal inequalities.

- *Economical.* Meeting the needs ensuring that the economic production is maintained in the long term.

In this context the United Nations Assembly sets in 2015 a collection of 17 Sustainable Development Goals (SDG) designed to achieve a better and more sustainable future for the world by addressing the challenges the world population face in terms of sustainability. The established objective is to meet all the goals by the year 2030; however this seems far-reaching for the actual system.

Figure 2: United Nations sustainable development goals

Circular Economy a system that is based on the minimization of resource extraction at the expense of maintaining the highest value and utility of products by extending their lifecycle trough value recovery propositions such as recycling, reuse, remanufacture or repair; as well as promoting the intensification of use and dematerialization of products by means of sharing principles. Appears as an ideal tool to promote the achievement sustainability, in fact a study that analyzes the potential of CE in meeting sustainability requirements [5] concludes that CE practices can directly contribute to achieve 5 SDG and also has potential to create synergies for other 5 SDG more.

The concept of Circular Economy that emerged time ago, is gaining popularity in the last years as it is becoming familiar within the general public, however despite its degree of conceptual development its application is still considered to be underdeveloped, the required actions to implement it are not being addressed and the consolidation of the system seems far in the future; as a matter of fact the world is considered to be just 8.6% circular, as of all minerals, fossil fuels, metals and biomass extracted each year just 8.6% are cycled back a number that is even lower than the one from 2017 (9.1%) [6].

Industry 4.0 as a sustainable tool

On the other hand technological innovations have served as optimization tools for development, by transforming the way the world operates. Information and Communication technologies have revolutionize the way people relates with their environments and now the fourth industrial revolution aims to transfer this paradigm of information to the industrial and manufacturing sector.

Industry 4.0 introduces a set of new technologies with Internet and networking as the main driving forces, where humans, objects and systems are represented physically and digitally around a supply chain that is able to dynamically organize and optimize itself through digital available information. Industry 4.0 is based in horizontal integration across the value chain; it facilitates the interaction between stakeholders along the product lifecycle trough continuous flows of data and information. A system with these characteristics appears as a proper tool for managing complex supply chain networks like the ones that implies Circular Economy systems.

However the progress that is being made in the implementation of 4IR technologies is still at the beginning and companies that are starting to introduce new technologies are doing it in a uneven manner, as production areas are starting to implement this new technologies but non-production processes are not jet being considered.

The interrelation between Circular Economy and Industry 4.0 is still an emergent topic as there is not a substantial amount of reports and real case studies; however the potential of the synergy of these two paradigms is undeniable and offers a promising future for research and development activities.

Goals and scope

This section aims to reflect the main goals that are intended to achieve with the writing of this paper, as well as the scope in terms of which are the constrains that have been considered in the development of the paper.

The theoretical nature of this paper translates the goals of the project to a series of key topics that should be addressed in order to effectively communicate the core ideas of the project. In this context the main goal that is addressed during the paper is: The review of the existing potential that Industry 4.0 technologies offer for enhancing the implementation of Circular Economy practices. The rest of the existing "goals" of the paper will derive from the main one with the intention of contextualize and develop the knowledge to address the main topic. The following could be considered as the secondary goals:

- Detailed definition and characterization of the concept of Circular Economy.
    - Description of the main working principles of the system, impacts and implications of the implementation at a social, economic and environmental level.
    - Analysis of the main enabling factors for the implementation of CE and the role of products in the transition to CE.
    - Analysis of the existing policies and barriers and the current methods for measuring the progress.
- Introduction to the main principles and characteristics of Industry 4.0
    - Definition and development of the concept, analysis of the key features and main innovations it introduces.
    - Description of the key technologies regarding technical description and possible applications.
- Review of the existing synergies between CE and Industry 4.0
    - From a theoretical perspective in terms of possible benefits and implications of the fusion of the concepts.
    - From a practical perspective analyzing the existing practical cases where Industry 4.0 technologies encourage CE practices.

In terms of the scope, in order to discuss some of the topics of the paper with a more concrete approach, a few of the analyzed issues have been particularized to certain geographical areas or economic sectors as it follows. For the description and characterization of Circular Economy, some of the considered topics have been limited to the European continent, as a global analysis would have supposed too much heterogeneity in the extracted conclusions. For the case of the description of the Industry 4.0 technologies, the focus is mainly given to their application in the manufacturing sector, as it is considered to be the more representative and an analysis of all the possible applications in more sectors would have required for a much more extended work. Also the number of Industry 4.0 technologies analyzed is restricted, and only the considered as more relevant for the paper are included.

For the case studies employed in the study to represent the synergies between CE and Industry 4.0, these have been limited to certain industry sectors as it is properly explained in the corresponding chapter.

With respect to the extension of the work, this has been limited to what usually is required for a Master Thesis and when some explanations were considered to be out of the scope, they have been gathered in the corresponding Annexes or referred to the existing literature.

Benefits of the project

In this chapter the benefits that can be extracted from the development of this project are outlined. Since the topic of the paper is merely theoretical the benefits can be considered in two ways: The first as the work is contextualized into the development of an academic formation, is focused on which are the benefits that the elaboration of this project has reported to the author, in addition it also evaluates how the work can contribute to the researched topics and what are the valuable insights that readers can extract from the reading. The second is about the benefits that this particular topic of the implementation of Industry 4.0 technologies in Circular Economy systems can have in areas like environmental issues, economic development or societal needs among others. The second is considered to be covered along the whole project so this chapter will be centered in the discussion of the first.

In terms of the benefits that the author has extracted from the elaboration of the project, it can be concluded that the main one is a significant understanding about the emergent topics of Circular Economy and Industry 4.0 and the possible synergies between the two. Also the author has gathered the required skills to elaborate a technical research paper, this includes: Adequate dissertation of valuable sources and adequate citation of the selected information sources, ability to successfully structure a scientific paper in order to efficiently transmit the core ideas of the project and the ability to draw original conclusions grounded in research.

Regarding the contribution of the paper to the researched topic. As mentioned before the amount of existing research is not broad, particularly for studies considering the subject from an overarching perspective. Thus the paper serves as a great source of review of the topic as it reflects some of the most recent and relevant studies. The project also presents a particular approach to the researched area, with the introduction of original and innovative case studies that properly reflect the potential of the subject and at same time are supported with a well elaborated theoretical background.

The detailed characterization of Circular Economy and Industry 4.0 serves as an introduction to the main topic and also facilitates the non-expert reader the comprehension of the core ideas of the project. The didactic way the project is approached enables the reader to acquire knowledge about the studied topics in a clear and organized manner.

Circular economy

Through this chapter the concept of circular economy is described as a whole. First a definition of the concept and its main working principles are outlined, then the impacts and implications of the accomplishment of this new system at a social, economic and environmental level are analyzed. Then the enabling factors for implementing this economic system along with a brief inside of the role of the products in the CE are outlined. Finally the policies and perceived barriers are considered as well as the existing tools for measuring the progress.

Definition and working principles

The concept of so called circular economy has been and still is one of the most resounding topics in the context of sustainability and sustainable development. However, outside of the academic and scientific world is not fully understood.

The term appeared for the first time used in an economic model defined by [7], the development of this new economic system was based on the idea that “everything is an input to everything else” and applied the principle of the first and second law of thermodynamics [8].

From this initial idea, similar terms differently named arise, (“Cradle to cradle”, “Industrial ecology “or “Blue economy”) these concepts can be considered as an intrinsic part of circular economy or as part of a more complex vision that enrich the concept. Diverse approaches to the concept have created different definitions through the years. The authors of [9] from a resource oriented perspective, suggest that the circular economy refers to the “production and consumption of goods through closed loop material flows that internalize environmental externalities linked to virgin resource extraction and the generation of waste (including pollution) [9, p. 49].’

Another commonly used definition is the one provided by the *Ellen MacArthur Foundation* which characterizes the circular economy with a more wide approach to the concept:

> An industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the

elimination of waste through the superior design of materials, products, systems, and, within this, business models [10, p. 5].

This definition extend the vision from the resource oriented idea to a more broaden one that drive the whole system to generate a positive effect in the natural and social capital. For the interpretation of the concept, [10] establish a distinction between technical and biological cycles regarding the materials used:

The technical cycle involves management of finite stocks. Technical materials are used not consumed. They are recovered and mostly restored in their cycles.

The biological cycle comprise renewable materials. These biological materials are consumed and are mostly regenerated within the cycle.

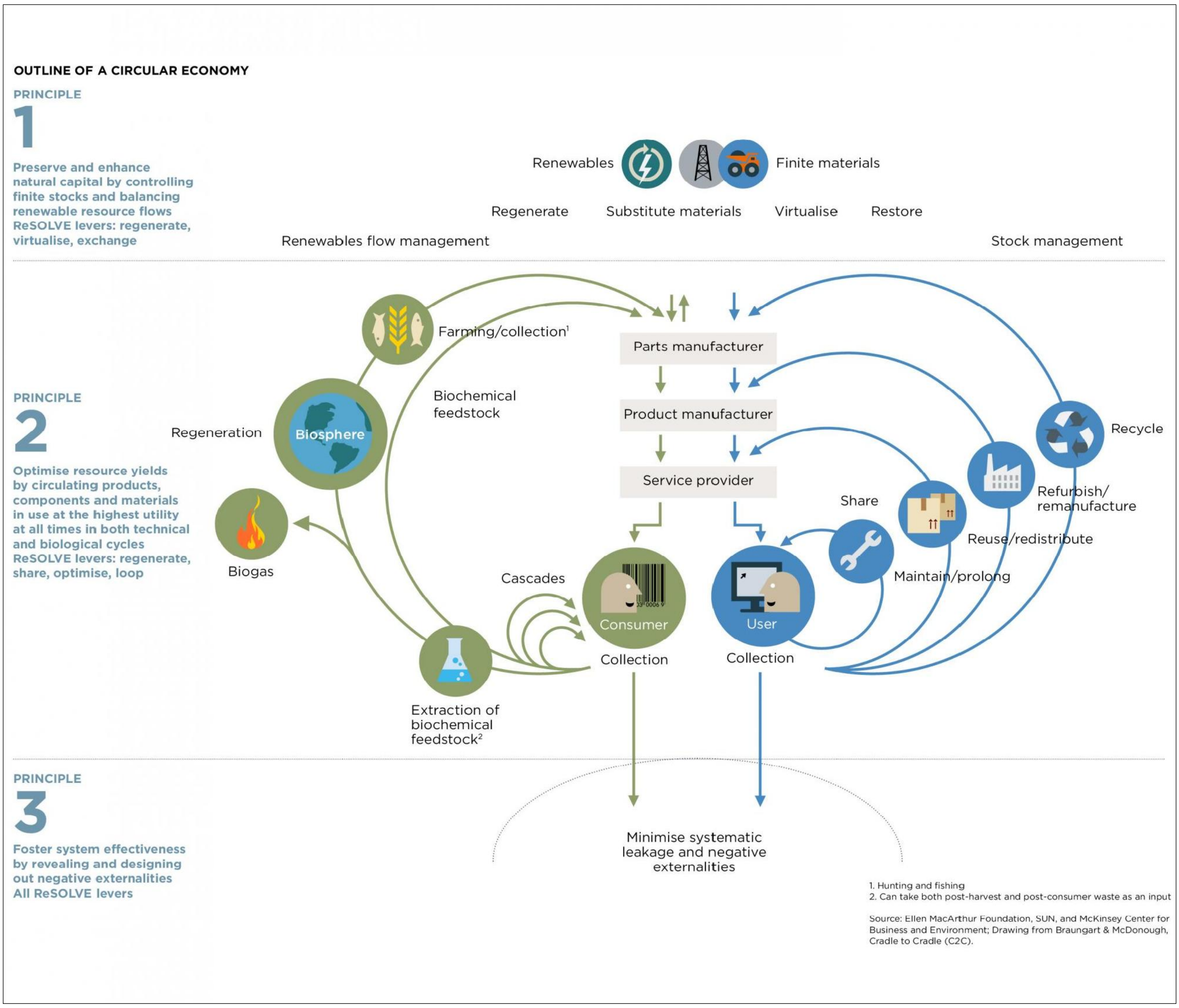

Figure 3: Outline of the circular economy.

Exploring more into the idea of circular economy, [10] establish three principles as the bases for taking action in the implementation of this new system as graphically shown in Figure 3:

Principle 1: Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.

Utility must be dematerialized as much as possible, virtualization and digitalization of products and services prevent resource consumption. When necessary the resources are wisely selected, they must be great-performing ones and renewables if possible. They should encourage flows of nutrients that enhance natural capital.

Principle 2: Optimize resource yields by circulating products, components and materials at the highest utility at all times in both technical and biological cycles.

Prioritize the product design for maintenance, remanufacturing, refurbishing and recycling, which keeps materials circulating into the technical cycles. Tighter inner loops will require less energy and material consumption to maintain the materials in the cycle. Extending the life time of the products will keep the inputs of resources to lower values and product share strategies will reduce the quantity of products manufactured.

Biological cycles allow nutrients to be recovered as new resources by decomposition. Products are designed to be consumed and regenerated through their lifecycle. For biological material cascading them through other applications enhance value creation of products and materials.

Principle 3: Foster system effectiveness by revealing and designing out negative externalities.

Reducing the negative externalities that products generate through their cycles in their environment. The impact that the products generate in all areas of their environment (food, health, ecosystems, social activities…) should be beneficial or with low negative impacts in the social and natural capital.

The above explanation gives a general overview of how a Circular Economy system should look like in the general terms, nevertheless the availability of strategies and approaches to its particular implementation will considerably differ depending on the concrete product or process. These ideas then serve as proper guidelines but each case will require for a specific analysis of the existing possibilities and the selection of proper strategies, as similar approaches will result in totally different outcomes.

Environmental, social and economic impacts

Moving from a linear to a circular economy entails a great transformation for the actual system, thus the possible generated outcomes of this drastic transformation should be addressed. In this section an analysis of the impacts that the deployment of a Circular Economy can generate principally at an environmental, social and economic level are analyzed.

Regarding economic and environmental issues, a recent study evaluated the impacts of the development in Europe of Circular Economy in the food, mobility and construction sectors [11]. The study predicts savings in the primary resource inputs of approximately 600 million euros in the European countries by 2030 and a reduction in greenhouse gas emissions of 48% by 2030 and 83% by 2050 compared with the levels of the year 2012, as well as the reduction of costs of externalities of 500 million euros by 2030. This study reveals, first the potential that CE practices holds to reduce the overall resource consumption and second, how the reduction in resource consumption is translated in a more environmental and economical sustainable system.

In a more social context in connection with job opportunities, there are some existing studies that suggest that the deployment of circular economy will generate a change of paradigm in the labor sector in terms of the performance and the skills needed for the new job positions. A study of the impacts of CE in the United Kingdom [12], estimated that around 500 000 new jobs could be generated in the country directly related with CE practices by 2030. This study also yields how different circular economy approaches will generate different types of jobs. Labor-intensive practices like sorting or preparation of materials for reuse will mainly require low-skilled workers while recycling, remanufacturing or bio-refining will require more skilled workers.

Furthermore, a report regarding future circular economy jobs [13], stated that 36 additional jobs will be generated per 10 000 tons of new recycled resources. Also the report highlights the fact that the declining of extracting jobs, the creation of new local economies trough close loop strategies and the embracement of digitalization and automation in manufacturing will drastically transform the job environment.

A more in deep report about environmental impacts [14], analyses the impact that CE strategies have in Carbon Dioxide (CO_2) emissions in the industry sector, taking in consideration four of the main materials of industry, that account for the 66% of industrial CO_2 emissions (steel, plastics, aluminum and cement) and two of the main sectors where they are used (passenger cars and buildings). The report indicates that even for an ideal scenario where decabornisation of processes like total electrification of transport, use of zero-carbon electricity, low carbon processes or carbon capture are implemented, the total reduction of CO_2 emissions won't be enough for keeping global warming below the 2ºC target of the Paris Agreement. Nevertheless the report estimates that in an ambitious scenario where CE practices are properly grounded, emissions of heavy industry can be significantly reduced as much as 296 million tons of CO_2 per year in the EU by 2050, which will suppose a reduction of 56% from the baseline scenario–and some 3.6 billion tons per year globally Figure 4.

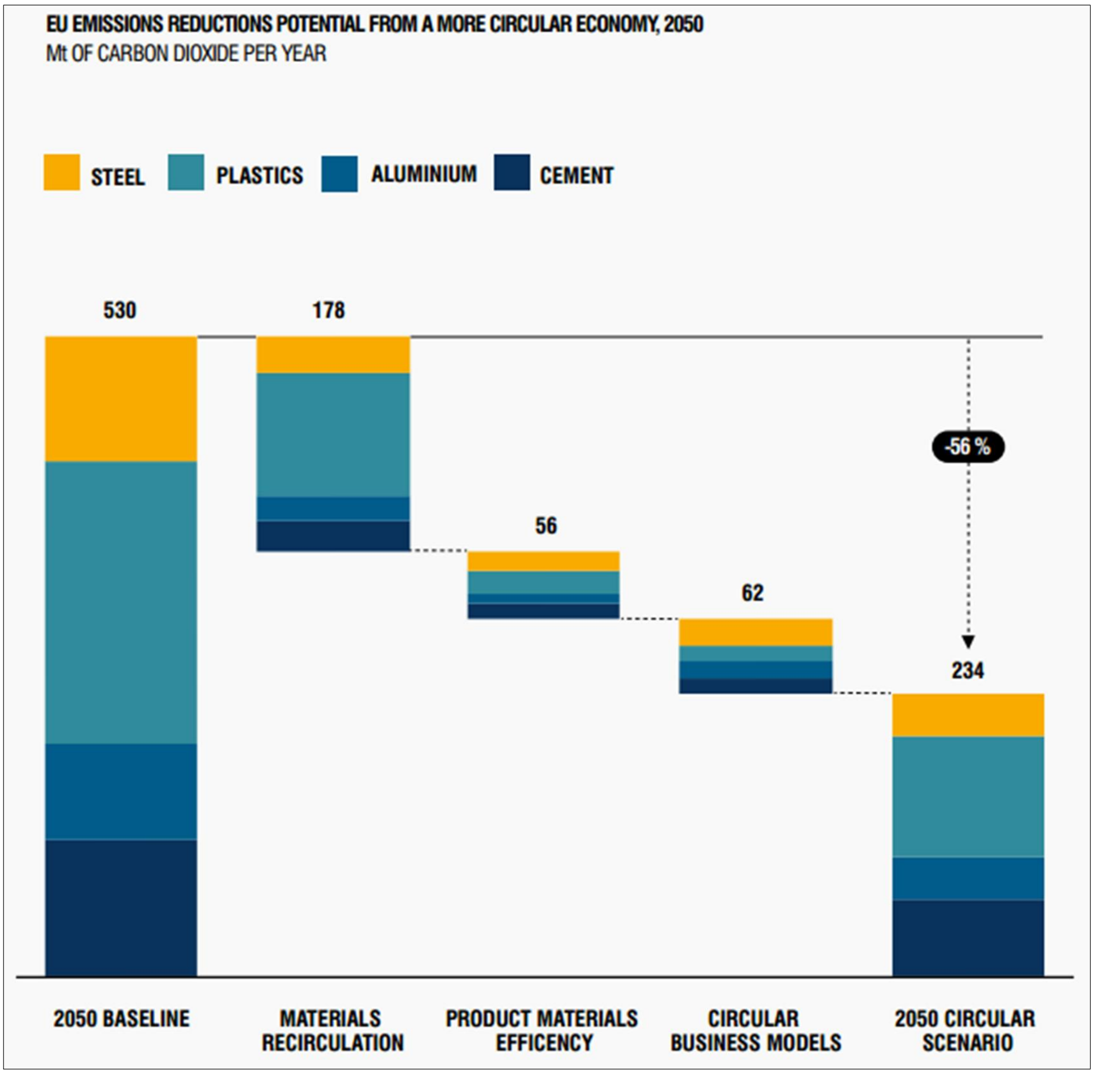

Figure 4: EU emissions reductions with Circular Economy [14].

The report also points out that by reducing the need for industrial processes associated with substantial air pollution, disease and mortality rate can be reduced. In addition reducing the need for mining will deplete soil and water pollution as well as the destruction of ecosystems.

In the same report [14] there is an evaluation of the potential for reducing emissions of three circular strategies: Material recirculation, material-efficient products and new circular business models. The Material recirculation strategy based on the establishment of high value recycling provided more than half of the potential for CO_2 emissions reductions. Material efficient products, based on manufacturing with less resources and employing improved production processes, along with circular business models like collaborative consumption or practices that promote long lasting products, accounted for the rest of the potential for reduction of CO_2 emissions at equal parts. One of the main reasons for which material recycling holds the biggest potential is due to the fact that the actual levels of recycling particularly in the studied materials are so low.

Circular Economy enabling factors

The transition from a linear to a circular economy requires for significant changes in many different socio-economic areas, involving social, economic and technical factors. A successful transition to CE is dependent on key strategies in certain areas that serve as foundation and generates value for the system.

The 2015 *European Enviroment Agency* report about the Circular Economy [15] aims to raise awareness about the potential benefits and the way through optimal implementation among policymakers, investors, businesses and consumers. In this context the report establish four key enabling factors to consider for a successful transition to CE:

Innovative business models

Business models play transcendental roles in any particular economic system as they principles have a direct and lasting effect on the system, innovative business model that successfully implement CE practices set the reference for the rest and generate competitiveness accelerating the transition, however this competition will only be possible if policies are adapted consequently. The following paragraphs examine some of the most promising business models for CE.

Service and function based business models.

Product as service models allows for a more close relation between producers and products along their lifecycle. In a new economy where producers are required to minimize the impacts of the products through their whole lifecycle, service models appear as a suitable way of managing the actions required to meet the market specifications. Whereas the product belongs to the producer or the consumer, the facilitation of maintenance, product upgrades or end of life collection requires for the company to develop a service oriented approach. Industrial companies in Europe are increasingly relating income with service provision. Accordingly to this fact, as [16] points out during a period of twenty years from 1995 to 2015 the income related to production has fallen from two thirds of the total to 56%, being service provision the rest of the total income.

Collaborative consumption

Collaborative consumption is one of the most consumer oriented approaches of circular Economy and emerging technologies based on digitalization are boosting its potential. Rooted on the principle of sharing, it maximizes the use of a product by allowing many users to access the shared product, this reports a series of benefits at an environmental and economical level, resource and energy consumption is reduced due to the minimization in production demand and the costs of access to the product are cut down. However, some collaborative consumption strategies can result in negative environmental impacts as they can promote an excessive usage of inefficient products, as can occur with an increase in mobility [15].

The act of sharing possessions and the change of attitude towards the acquisition of services beyond products have gained approval through the years, in fact a survey conducted in Europe in 2014 showed that 54% of the respondents were willing to rent or share their possessions for money and 44% were willing to rent from others [15]. However, a recent *Eurobarometer* conducted among European citizens [17], indicated that just 23% of the respondents have used services offered via collaborative consumption. Among those users of collaborative platforms, over half have accessed services in the accommodation (57%) and transport (51%) sectors; but very few reported to have used these platforms on regular basis, at least once per month (4%).

Waste as a resource business models.

The waste generated during the lifecycle of the product, can generate new business opportunities by promoting markets for secondary raw materials across sectors [15]. Companies that enhance this type of business acquire economic benefits from the normally cheap input of waste; additionally they acquire a green reputation, that today stand out as a great competitive factor [18].

Waste recovery activities implies an overall safe in resources, however the form of this recovery determines the value that can be generated. As mentioned before, tighter loops are always preferable for the majority of the cases, recycling activities normally require for considerable amounts of energy inputs, so reuse and remanufacture processes are always preferred. In any case a CE system will require for all forms of recovery in order to maximize the value of materials along their lifecycle.

New job opportunities and a great amount of turnover are expected to be generated in this sector in European countries. Also a possibility of saving arises in developing countries as is common that from 20% to 50% of the municipal budget is used for the solid waste management [18].

Financial mechanisms

In terms of financial matters the cash flows and investment rates will considerably change. For businesses that acquire circular practices where the property of the product remains with the manufacturer, a need for a greater investment at the beginning will be needed, as the acquisition of new mechanisms for managing the whole lifecycle of the product will suppose a greater expenditure. Also the cash flows will change as payments will arise in different phases of the lifecycle and the purchase of raw material will be reduced.

Eco-design

Most of the product costs and environmental impacts that arise during the product life-cycle are determined in the development or design phase of the product [19]. Along with the fact that the development of the product is where changes are more easily accomplish, this makes the design phase a key enabler for circular economy practices.

Currently there are some design approaches that fits well with the CE strategies: Eco-Design, design for X ideas (being X: Environment, sustainability, recycling…), Life Cycle Design or Green Design. Of all of them Eco-Design is considered the most extensive term as it gathers the main ideas of the rest.

A definition that condenses well the essence of the eco-design strategy is the following:

> The integration of environmental aspects into the product development process, by balancing ecological and economic requirements. Eco-design considers environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle [20].

The main purpose of eco-design is to create products that comprise the use of fewer resources, prioritizing renewable and recycled when possible and avoiding hazardous materials. Also the design should consider the products' maintenance, reusability and recyclability by designing components that last longer and facilitate these practices [15].

With a more wide vision of the integration of product design in the CE, the authors in [21] propose a design framework in which there is a two level strategy of design for technical or biological cycle and each of them is divided in two different strategies shown in Figure 5.

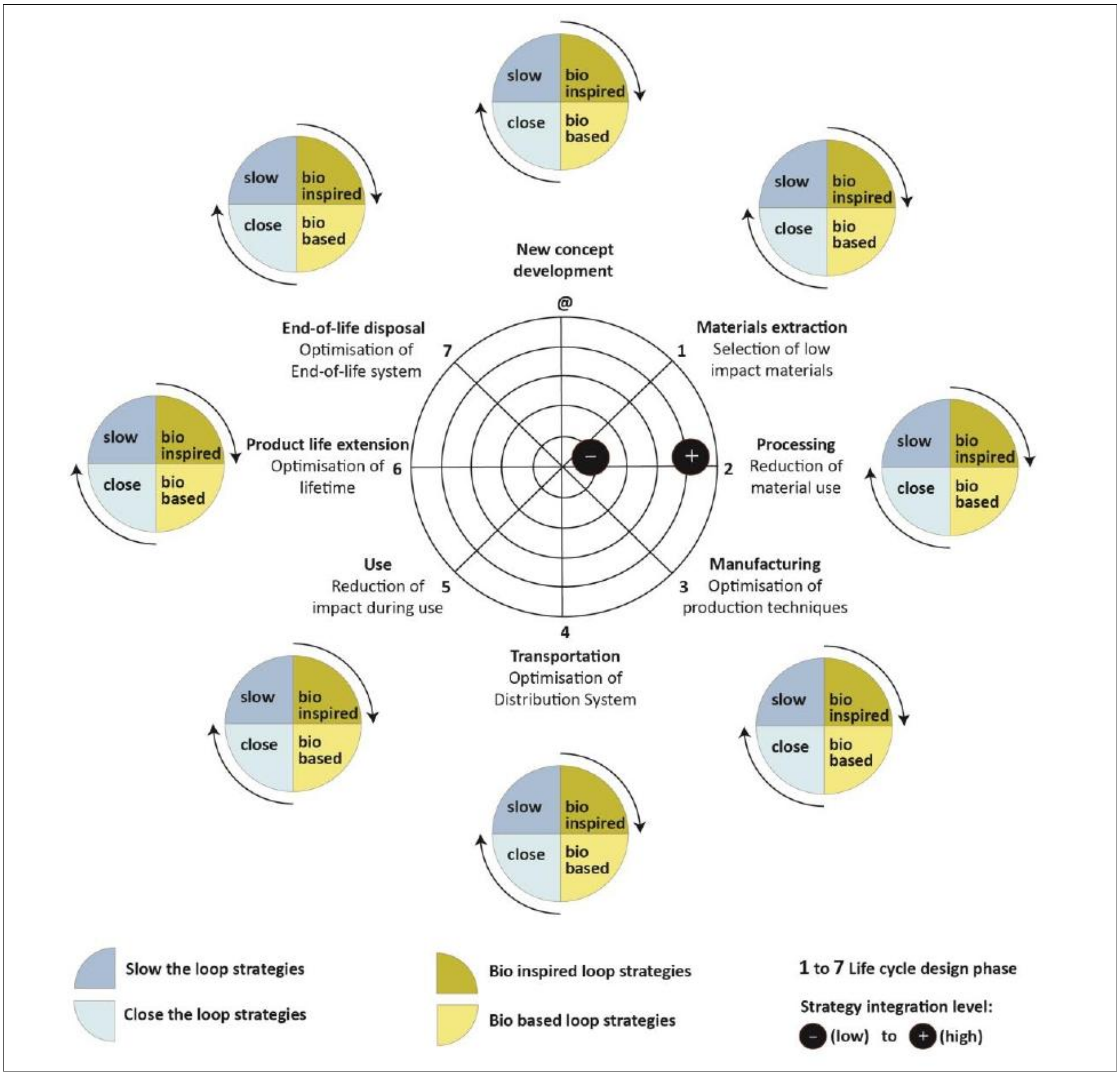

Figure 5: Multiple loops Life Cycle design strategies [21]

Design for a Technical cycle has the aim of minimizing material and energy inputs and emission outputs along the product lifecycle, while maximizing the product value. The two proposed strategies are:

1. Slow the loop strategy. Slow material flow in each phase designing for durability and life extension, it also involves adding value to the user with approaches like emotionally durable design.
2. Close the loop strategy. Maintaining the value of the materials by designing for recyclability allowing for disassembly and proper material selection.

Design for a biological cycle. Represents the biological design solutions inspired by nature, tackled with two strategies:

1. Bio-inspired loop strategies. Designing products that imitate nature, addressing human engineering problems with the study of natural systems.
2. Bio-based loop strategies. Aim to utilize biological materials that can be returned safely to the biosphere at the end of their lifecycle.

With this approach the authors stablished a set of actions to perform along all the product lifecycle for each of the four different level strategies that are gathered in the Appendix1.

Extending the lifetime of products through reuse and repair

The lifetime is defined as the time interval from when the product is sold to when it is discarded. The expansion of the lifetime of a product is directly linked with the amount of resources that a consumer is demanding while using a certain product. Reuse and repair activities enable the extension of the product lifetime as well as generate profitable economic impact with the creation of new job markets and opportunities.

Products designed for being repaired have much more possibilities of extending their lifetime. In the context of product as services, repairing activities are easily conducted, as the manufacturer, owner of the product, is an expert of the know-how and has more facilities in accessing the spares. The reuse of products should always come first within the strategies for recovering value from a disposed product. As less resource inputs are required to keep the product running again. However, it is a fact that today's markets do not allow to a great extent the possibility of reuse in certain products, as the short innovation cycles and rapidly changing market fashions result in the premature discard of products.

Despite this, markets for second handed material have been incremented due to the facilities that arise in internet platforms where there is no need for intermediaries to sell used products. In addition the new concept of centers for repairing products are paving the way through allowing the consumers to repair their own products without the need to expend much money on it.

Nevertheless, for some existing products the use phase of the product accounts for most of the environmental impact, in this case extending the lifetime of the product is not the most advisable strategy. Improvements in technology that allows for a reduction in the impacts of the use phase may suggest a redesign of the product rather than an extension of their lifetime.

Waste prevention programs

In the year 2016, nearly 2.5 billion tons of waste was discarded in the *EU-28*, 101 million tons of which were hazardous, the total value is slightly lower compared to the year 2004 but the growing tendency has been stablished since the year 2008 [22].

Managing the waste generated along the lifecycle of the products, and particularly in the end of life (Eol) scenarios, is of great importance. However, prior to manage the waste, the implementation of actions to avoid unnecessary waste should be confronted. Minimizing material content in the product will reduce the quantity of waste generated. Optimizing the efficiency of the process production processes should generate less scraps and discards. Avoiding the usage of hazardous materials and excessive product package will reduce the generation of unnecessary waste and will improve the material sorting. Company strategies like lean production, where avoiding excess inventory and equipment are prioritize; will certainly reduce the waste generated during the production process [23].

All along with repairing, reusing and recycling practices will reduce the amount of waste generated, changing the perspective of what is real waste and can be discarded and what can be seen as a new resource.

In the context of waste prevention, policy measures are of great importance. *The EU´s five-step waste hierarchy* established in the *2008 EU Waste Framework Directive*, determined a hierarchy action plan where avoiding waste generation is set as a priority followed by preparation for reuse, recycling, recovery and finally disposal.

Products in the Circular Economy

Products play a very important role in the transition to Circular Economy, maintaining the value of the products by extending their lifetime while using as less resources as possible will require for a fundamental change in the way products meet the customer demand. However, prior to this a transformation of the societal production-consumption systems is needed. This transformation will not only require for technological innovations; application of novel social practices, new business models and a change in consumer behavior will be needed. Policies plays an important role for this transformation as they would have to be adapted to offer the maximum competitiveness to the circular products.

In [24] an overview of the mechanisms that shape the role and fate of the products in a linear or a circular economy are explained from three different points of view: business selling products, consumers buying products and policymakers regulating the production. These key mechanisms are summarized in Table 1.

Linear system mechanisms	Circular system mechanisms
Business perspective	
Products as value creation source Profits are the difference between market price and production costs. Technological innovation makes products obsolete urges consumers to buy new products. Intellectual property rights main source of value, protective design measures barriers for repairing.	***Functionality source of value creation*** Business models focus and compete on adding service value. Technological innovation adds extra value by solving societal needs. As products belong to companies, cost minimization drives extension of product lifetime (reuse, repair and remanufacture).
Economies of scale in global production chains Cost efficiency drives the optimization of global production chains, minimizing the costs of resources, labor and transport.	***Location of production and use tend to be more linked*** As service provision of physical products is linked to the costumer location. Local production and management is promoted.
Steer consumer needs towards product offer Products with short lifespans are preferred as	***User needs/wants drive the role of a product*** Offering the best service means matching the

	they are cheaper to make. Maintenance and repair are avoided, as it is more profitable to sell new products.	(intangible) needs of the user with a combination of services and products.
	Tendency to disregard end-of-life phase There is no economic incentive for product life extension, reuse or remanufacturing as they counteract most linear business models.	***Internal incentive to incorporate end-of-life phase in business model*** As products are assets, minimizing life-cycle costs is an implicit incentive for a company, inducing a search for the best economic equilibrium between reusing, repairing, remanufacturing and recycling products.
Consumer perspective		
	Consumerism follows marketing Consumers want new products that keep pace with fashion and technological advances. Consumers must match their needs with the product offerings available.	***Customer satisfaction is an important driver*** In a service relationship, the customer experience feeds back strongly, raising consumers' awareness of their actual needs. Consumers can become prosumers who co-create or co-produce the products and services they need.
	International opportunities for cost reduction Consumers seek the cheapest version of a product on international markets, enabled by e-commerce.	***Local-first attitude*** Accessibility to the service provider is part of the service experience, which leads to proximity as a customer choice criterion.
	Ownership is the norm Owning a product is the normal way to fulfil needs. Over time, previously luxury products become commodity goods due to decreasing production costs. Beyond legal warranty, product repair is too expensive compared with buying a new product. Do-it-yourself repair is considered too difficult due to complex and protective product design.	***Accessibility is the norm*** Fulfilling needs is driven by accessibility of a product and its use satisfaction. Different consumer segments can access products of their choice through customized services or by sharing products. Service agreements provide an incentive for product care for the producer and the user.

Low/no residual value of products End-of-life products are considered a burden, to be disposed of as cheaply as possible by selling on the second-hand market, storing at home, or through regulated waste disposal systems or illegal incineration or dumping.	***End-of-use incentives incorporated*** If products are part of a service, there are incentives to return them to the provider after use, avoiding stocks of obsolete products in households, or illegal dumping.
Policy perspective	
Dependence on existing production system Mass production of goods is strongly linked with the focus on cutting costs, and achieving efficiency, often resulting in lower labor costs and less job creation.	***More focus on facilitating skilled workforce*** More localized and service-based activities require a skilled but affordable workforce. Policymakers can facilitate this by shifting taxes from labor to resources.
Global playing field Competition for economic factors on the international market steers national social and environmental policies.	***Less risk for outsourcing jobs*** As management of products as local assets is less likely to be outsourced, there is less incentive for a race-to-the-bottom in social and environmental policies.
Balance consumer protection with economic stakes Protection of consumer safety and health is mostly reactive and geared towards protecting existing economic stakes, such as value-added tax (VAT) income.	***Facilitate safe and healthy services with regulation*** As safety and consumer health are business incentives for high-quality performance, policies focus on facilitation of these types of services.
Action prompted by health or environmental concerns There is no inherent incentive for regulation of the waste phase of products. Only when waste-related health or environmental concerns arise is regulatory action taken to minimize negative impacts.	***Facilitation of end-of-life management*** Extended producer responsibility rules create incentives for companies to internalize end-of-life management. Governments provide basic infrastructure and fiscal measures supporting reverse logistics.

Table 1: Key mechanisms shaping the role of products in circular and linear economies

Policies and barriers

European policies for Circular Economy

Policies are key factors in the development of CE strategies as they will smooth the way for companies to adopt this new idea of business models by promoting or forbidding certain business activities. In order to advance, in an efficient and reliable manner from the actual linear system to the pursued circular one, continental, national and regional policies should pave the way for producers and consumers to adequately integrate themselves into this new system.

Setting policies that successfully adapt and align to the demands of the system always require for valuable information of the surrounding circumstances. Current available information about circular economy in Europe, principally concerns data related with material flows and waste generation [25]. For that reason, the majority of environmental related policies focus on the end-of-life stages. Waste statistics do not include details about the quality of the recycled products or the level of material functionality retained, that is why existing policies are rather volume based than value based, this ends up with a system that promotes low–value materials with a low environmental performance [25].

Adequate policies require for proper assessment an evaluation of the progress. If progress wants to be properly assessed more precise product-level rather than material-level information is needed. Indicators that measure the rates of product reuse, repair or remanufacture along with monitoring product share practices, will provide a much deeper understanding of the actual state of progress of the CE practices in the system. That will unleash policies better aligned with the current situations and more effective in the accomplishment of the targets.

According to a study of the Circular economy Strategies in Europe [26] the strategies for the transition to a circular economy differ considerably in each territory, as the opportunities and challenges depend on factors such as population density, natural resources, industrial clusters, etc. All across Europe, countries, regions and cities have elaborated or are in the process of elaborating strategies that address the transition from multiple points of view in one document. In the documents, all stages of the value chain are considered and their main topics are:

- Provide a framework for ongoing activities in different sectors, by different players, and at different stages of the value chain.
- Provide a common objective for each activity setting the ground for assessing progress.
- Describe ways to further support the transition to a Circular Economy, documenting instruments and defining roles for making the transition.
- Function as source of inspiration to get people involved in the transition by expressing ongoing or prospective ways to contribute.

The number of strategies has exponentially grown since the year 2015 and as shown in Figure 6 the implementation along Europe is becoming widespread [26].

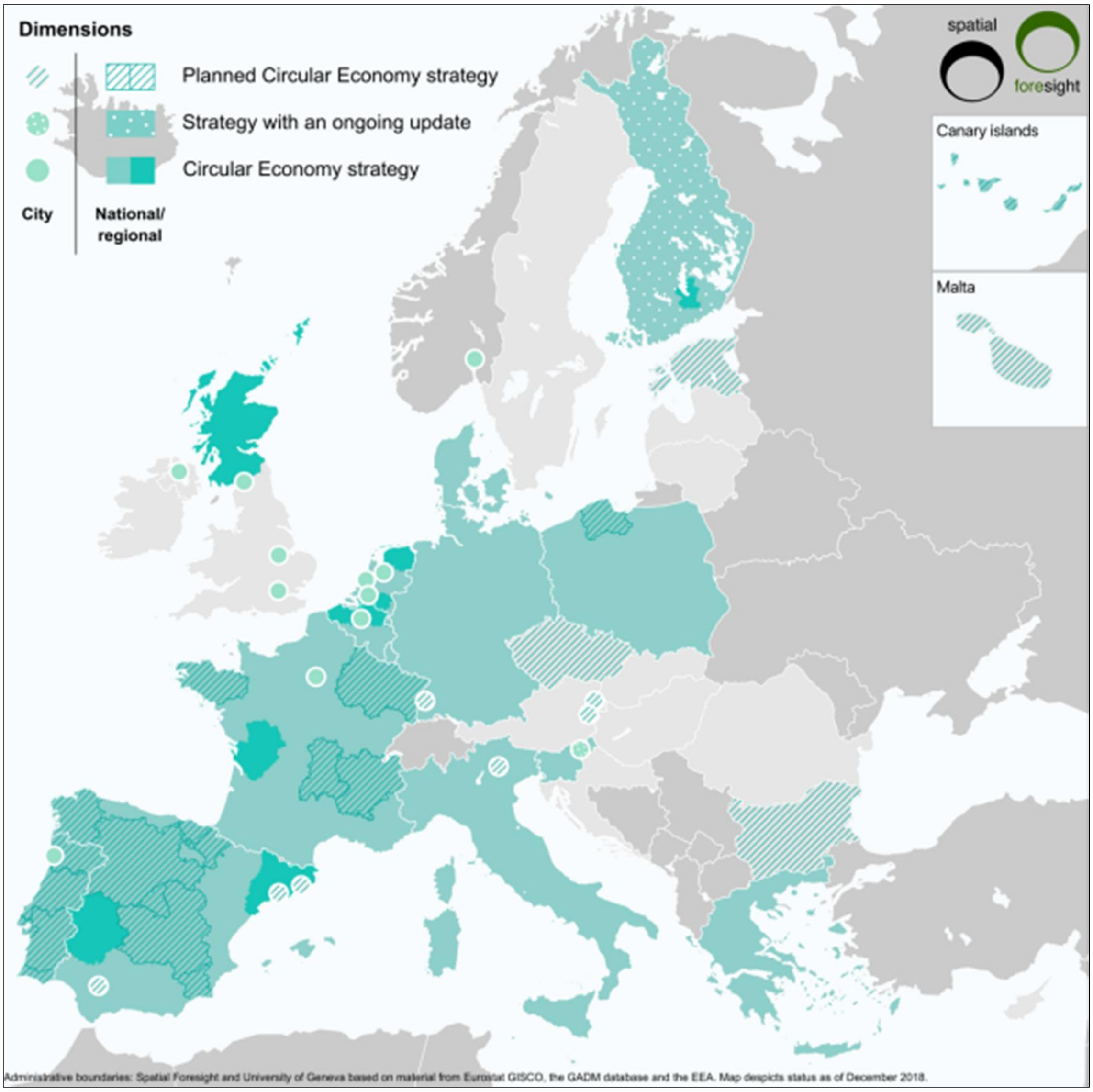

Figure 6: Overview of existing and planned circular economy strategies in Europe [26]

Perceived barriers and current performance of Circular Economy

A conducted study concerning the perceived barriers to implement CE practices [27], asked business experts and policy makers which were the most limiting factors in the integration of the concept. The main results exposed that: Cultural factors represent the biggest obstacle to CE, particularly the lack of consumer interest and awareness (47%) and the hesitant company culture (46%). Also the low virgin material prices remain particularly as a barrier in the policymakers' perspective (62%). In the other hand the ability to deliver high quality remanufactured products (11%) and the limited standardization in the market (14%) where not perceived as challenge.

According to these results, the reason CE practices are not currently being implemented is due to the fact that the cultural basis of society about this topic is still weak or is not fully grounded. Furthermore, the technological requirements for developing a circular system are not perceived as a challenge despite how far from reality CE might seem to be.

However other studies [28] [29] address technological issues as main barriers. This considerable difference may be explained as the fact that the existing technology can enable particular key operations of CE as recycle, reuse or remanufacture, nevertheless, in a short term vision there is still a lack of technological tools that allows to integrate these operations in a system that works efficiently and can function with guarantees.

A recent *Eurobarometer* conducted among companies across *EU28* countries [30], outline some facts of the actual performance of companies in circular economy practices. Large companies are taking actions principally for obtaining resource efficiency, 80% are minimizing waste and 59% recycle by reusing generated waste by the company as these aspects normally lead reductions (53%) in the production costs. However, just 27% of the companies design products that are easy to maintain, repair or reuse and just 30% sell crap to other companies. All these values are slightly reduced for SMEs and considerably change depending on the sector and country where the company works.

Other interesting fact highlighted by [30], is that the majority of European SMEs (63%) do not currently offer green services or products, and have no intention to do so in the near future. And those offering green products and services (24%), report that these account just for a small proportion of their annual turnover.

What can be concluded from these results is that circular practices are normally carried out because they entail economic benefits and do not necessarily mean that companies have a more sustainable attitude towards their businesses.

Measuring circularity

In order to build a solid circular economy system, the measurement of the performance of circular systems and products becomes a key factor, as it enables a process of internal and external evaluation of the involved stake-holders that contributes to the improvement of products and processes.

However, the large amount of inputs and outputs of energy and materials that products involve through their whole lifecycle suppose a challenge in the measurement of circularity. In this section some existing methods for measuring circularity will be presented, first at a micro-level measuring the circularity of a product or a business practice and then at a macro-level as the way of measuring circularity practices in a country.

Micro-level circularity evaluation

The measurement at a micro-level is supposed to serve as a tool for business to assess their own progress and for third parties to compare the performance of different companies. The authors in [31] analyze three of the existing tools for measuring the product circularity:

1. *Material Circularity Indicator (MCI).* Developed by the *Ellen McArthur* foundation to asses European companies about their product and business circularity. Is particularly intended for use in product design and is based on an excel calculation sheet, where the materials are evaluated by introducing information about the material origin and destination and the percentages of recycling reuse and the efficiency related.
2. *The Circular Economy Toolkit (CET).* An assessment tool to identify potential improvement of product circularity. The necessary inputs are the answers to 33 questions divided into categories related to different product lifecycle stages that evaluate the performance of the product in each stage.
3. *The Circular Economy Indicator Prototype (CEIP).* Similar to the previous tool aims to evaluate the product performance by answering 15 weighted questions divided into 5 lifecycle stages that provide a score of the product in each different stage.

These three tools hold different abilities of measuring circularity as *MCI* provides a rapid comparison between the performances of two different materials; on the other hand, *CET* and *CEIP* are more product-centric and lifecycle thinking oriented [31]. Although the tools serve as a rapid overview of products' circularity they are still far from accomplishing a robust measurement of the paradigm of circular economy as they fail in provide in advance fate of the products and the indicators make use of abstract information.

Macro-level circularity evaluation

Regarding the analysis of circularity at a macro level intended for the evaluation of countries or regions to serve as tool for the development of efficient policies, The *European Commission*, through the statistic platform *Eurostat*, has developed a monitoring framework that pretends to measure the progress of the European countries in terms of circularity [32].

For this purpose, ten indicators where selected as the most representative in the measurement of the progress. The indicators can be classified in 4 different categories and are shown in Figure 7.

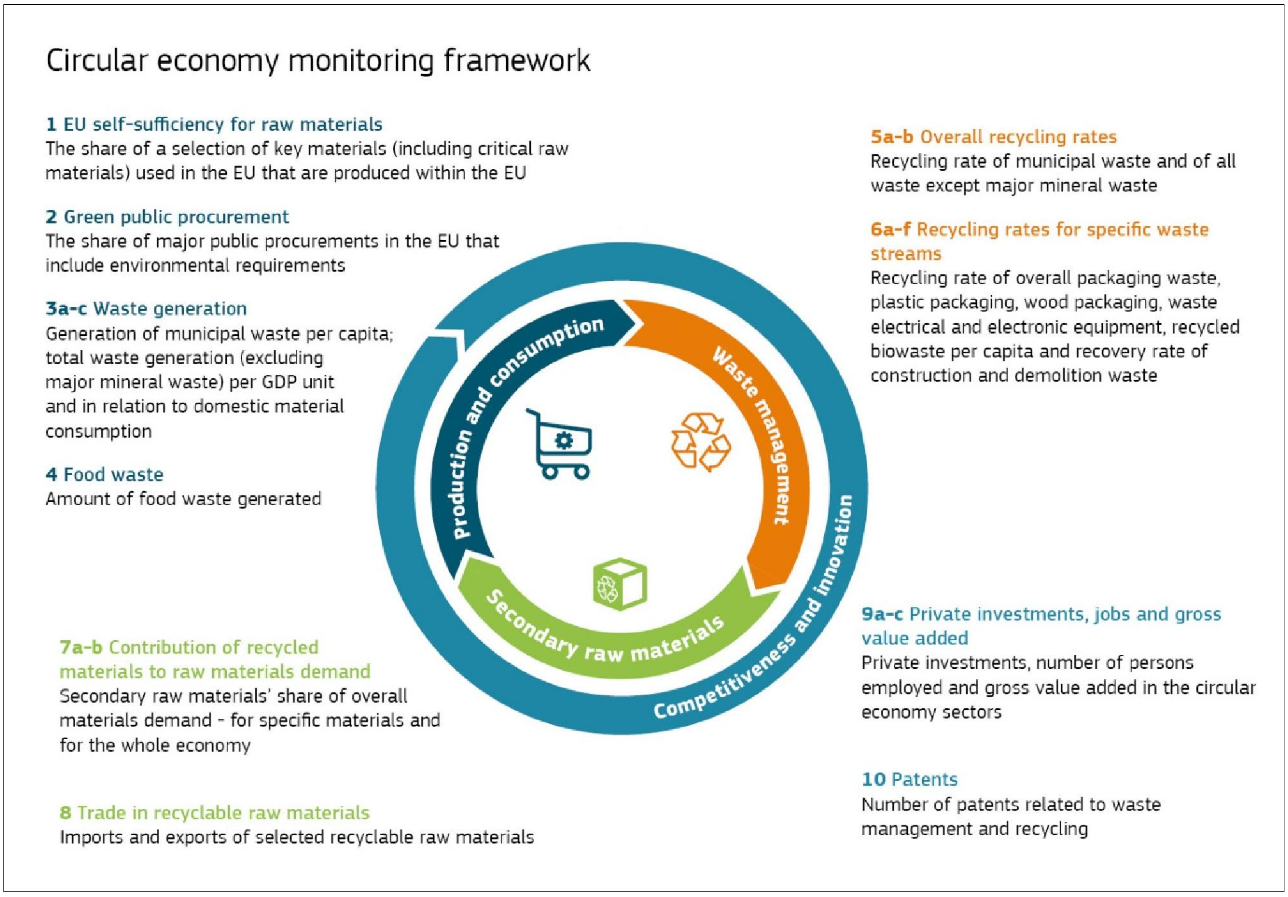

Figure 7: Circular economy monitoring framework [32].

Some of these indicators are still under development (2-Green public procurement) or their available data is not fully representative (4-Food waste). Analyzing the measurable ones, several findings can be outlined:

- All indicators related with waste measurement can be misleading as the methods of measurement between countries are not exchangeable.
- For the majority of indicators the differences between countries are substantial, this is result of an unequal degree of development between the countries and the approach of each country in the field of the indicator.
- The overall results from most of the indicators follow a similar trend. An initial improvement of the results is followed by a smooth out or decrease during the more recent years.
- The most remarkable good performance indicators are:
  - 5a) Recycling rate (in %) of municipal waste. Account for a 20% improvement during the last years (2000-2018).
  - 6-Recycling rates improvemnts (in %) for specific waste streams particularly: b) plastic packaging (17% from 2005 to 2017), d) e-waste (11% from 2010 to 2017) and e) Biowaste (31% from 2000 to 2018).
  - 10-Number of patents related to recycling and secondary raw materials. Experienced a growth of 17% from 2000 to 2015.
- The indicators that did not progress considerably:
  - 3a) Generation of municipal waste (kg per capita). With a slight reduction form the year 2000 (513kg) to 2018 (492kg) but with an increment from the year 2013 (478kg).
  - 7b) Circular material use rate (in %). With an increment of 3% from 2004 to 2013, but any more improvement until 2017.

As an overall conclusion that can be drawn out from the performance of these indicators: There is a slight improvement in certain areas of circularity in Europe; these improvements differ considerably between countries and the evolution of their performance has been considerably affected by the recent economic crisis. Also, the information that these indicators provide serve as a straightforward account of the actual system performance but is far from precisely measure circularity in countries, so the results must be cautiously taken into consideration.

Industry 4.0

Introduction

When past generations wondered about the future of today, they predicted flying cars, underwater cities or space tourism. We are still far from these realities; however, the progress made in Information and Communication Technologies has drastically transformed the actual way of living and still has much more to offer.

The fusion of the digital and the physical world has become a reality thanks to the technological breakthroughs in the field of Information and Communication technologies, leading to the development of new services and applications. Smart devices (devices connected to other devices or networks) interact with their surroundings to assist their users in the performance of a broad variety of tasks around different working areas. Transferring this connectivity to the industrial sector more precisely to the manufacturing processes is where the concept of industry 4.0 arises.

Following the first industrial revolution in the 18th century with the introduction of the steam-powered machine, the second starting in the 20th century with the first production line and electrically-powered mass production and the third in the year 1970 with the introduction of the first Programmable Logic Controller (PLC) leading to the use of electronics and IT to achieve automation in the systems. Today appears the concept of this so called Industry 4.0 or fourth industrial revolution.

The term Industry 4.0 was first introduced in the year 2011 by the German government to face the challenges of the actual manufacturing system in meeting the new demands of the society and it is intended to replace the actual production system that is becoming obsolete in dealing with the complexities of the actual market demand.

The aim of this new production system is to work with a higher level of automatization by bringing computerization and inter-connection to a "smart factory", that allows for a self-working and self-learning environment. The ability to monitor and control all the processes along the product supply chain via data generation and acquisition, will allow for an overall improvement in operational productivity and efficiency.

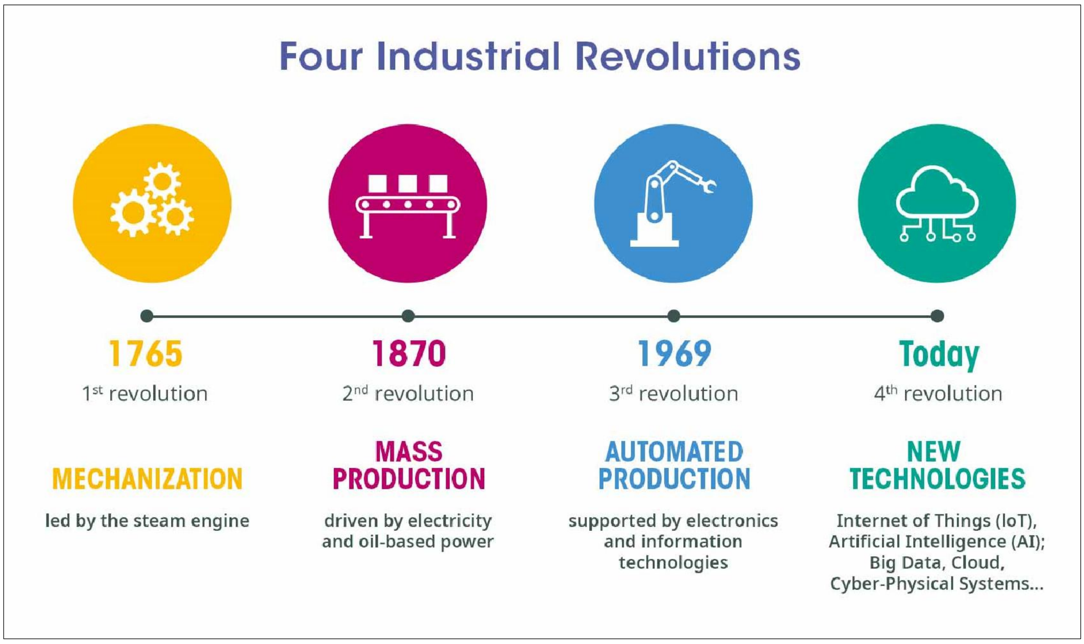

Figure 8: The four industrial revolutions.

A straightforward description provided by [33] assumes that this new industry can be considered as Cyber-Physical Systems (CPS) (physical devices and processes that integrate computation and networking capabilities), connected to an heterogeneous data and knowledge structure where the manufacturing process is integrated, optimized, adapted and service oriented, through the use of algorithms like BigData (BD) and advanced technologies such as the Internet of Things (IoT) and Services (IoS), Industrial Automation, Cybersecurity (CS), Cloud Computing (CC) or autonomous Robots.

During the following chapters a more in deep explanation of the main features and characteristics of the fourth industrial revolution along with the characterization of some of the above mentioned technologies will be provided.

Vision and features of Industry 4.0

Industry 4.0 aims to create smart ecosystems where every component of the supply chain is able to transmit and receive information and operates in consequence, achieving a system that is able to effectively control and manage all the working pieces of the production system. This vision of the future of manufacturing systems is according to [34] addressed by the following four main aspects:

1. *Smart Factory*. Aims to create a smart environment where flexible and adaptive processes are enable through the integration of smart solutions. Smart factories consist on coordinated intercommunication between all the manufacturing resources, as result manufacturing efficiency is increased and highly complex market requirements can be addressed.
2. *Smart products*. Integrated with the whole value chain. Trough data acquisition and storage are able to automatically monitor their own production stages request the required resources and control the production process. As final products should be self-aware about their parameters within they should operate providing information about their status during the whole lifecycle and able to autonomously interact with their environment
3. *Business models*. The new communication paradigms along the value chain will entail big changes in the way business operate. New business models arise with the opportunities that the new systems bring in terms of optimizing the system and creating interconnected environments.
4. *Customers*. Are benefited from the improvement of communication along the value chain. Real time requirements change could be provided duet to the high level of integration and smart products will provide information to users about status, utilization parameters or dispose instructions that will enhance the user experience.

Other characterization of Industry 4.0 is its level of integration along three different dimensions. Horizontal integration refers to the integration of all the resources, information flows and connected networks within an organization and between organizations that can occur at different levels such as production floor, production facilities or entire supply chain. Vertical integration consists on the connection of all the manufacturing systems through all hieratical levels within the organization. The third level of integration known as end to end digital integration refers to the digitalization of the whole value chain as a combination of Horizontal and Vertical integration.

Key Industry 4.0 technologies

The number of technologies that Industry 4.0 embraces is not rigorously defined and differs from different publications, during the following chapters a selection of these technologies is introduced, this selection is based on the relevance the technologies have on the implementation of Industry 4.0 ecosystems and the degree of innovation they introduce. For each of the selected technology the explanation scheme is similar, first an introduction and definition is given, then a brief analysis of their working structure and components is given and finally some applications are presented.

Industrial Internet of Things and Cyber-Physical Systems

Internet of Things

Internet of Things has been identified as one of the technologies with the greatest potential for the near future; in fact a study predicts a potential impact of generated value of 11.1 trillion dollars for the year 2025 across nine different sectors from homes to factories [35]. The concept of Industrial Internet of Things (IIoT) is unambiguously related with the concept of the Internet of Things, as the first is just a particularization of the latter, in fact [36] outline the lack of clear definitions about IIoT, as the existing ones are not fully representative of the distinctions between the two. With that in mind, a proper definition of IoT will be the foundation for the introduction of the concept of IIoT.

IoT can be thought as a system where physical "smart objects" receive and transmit information through their embedded sensors and are connected to the internet or a network where they are uniquely identified and share their data about their operational state through a platform.

The communication between these so called smart objects is present in many different domains, from home applications, where digital smart assistants regulate the temperature or lightening of the house with the usage of a mobile remote app, to manufacturing processes where machines provide real time data about their performance and their maintenance requirements.

The working structure of the IoT systems is gathered in what is known as the design architecture; prior to its definition some key components should be defined:

The Sensor network. This network consists of various sensors that measure same or different inputs and communicate with each other normally trough wireless connections [37]. These networks have existed long before IoT as ways of monitoring environment, physical forces, etc. Today, their measurement principles remains similar, however, is the purpose of their outputs what has considerably changed. As intrinsic parts of the IoT structure their measurements are not only used for monitoring purposes, but to generate an actuation in response to the measured parameters.

Radio-frequency identification (RFID). Is also a key component of IoT. It has the purpose of transmitting the unique identity of an object. An RFID system consists of a RFID tag attached to an object and RFID reader in charge of identifying the object. The fast and proper identification of the objects allows for many working possibilities in IoT.

The design architecture of IoT should be able to bridge the gaps in the operation from physical to digital world. More particularly, service oriented architecture guarantees a proper communication between heterogeneous devices in multiple ways and enables the upgradability of the hardware and software components [38]. A four layer commonly used architecture proposed by [38] is graphically represented in Figure 9and is explained as follows:

- *Sensing layer* consists on tags or sensors that gather data from their environment and exchange it with devices. The advancement on RFID and sensor technology allows for the incorporation of information from new sources and in a more precise way it extends the capability of IoT as every connected thing to the system is uniquely identified.
- *Network layer* is the place where the connections are made. All the connected devices share information with each other and with existing IT infrastructures trough wired or wireless networks; then data is transmitted to decision-making units for the high-level complex services. The network should be able to map the connected things and to assign those roles automatically enabling devices to perform tasks collaboratively. In this context information confidentiality and human privacy security are critical.
- *Service layer* relies on the middleware technology that is the platform which provides support to the services and applications required. The middleware should be able to provide all the aspects required by IoT. Services run directly on the network to locate new services for an application and retrieve metadata dynamically. All of the service-oriented activities (information exchange and storage, communication, search and management of data…) are performed at the service layer.
- *Interface layer* is needed to make the interconnection and management of the connected devices easily and intuitively for the user. When large amount of devices provided by different vendors are involved, the compatibility issues must be addressed by the interface layer.

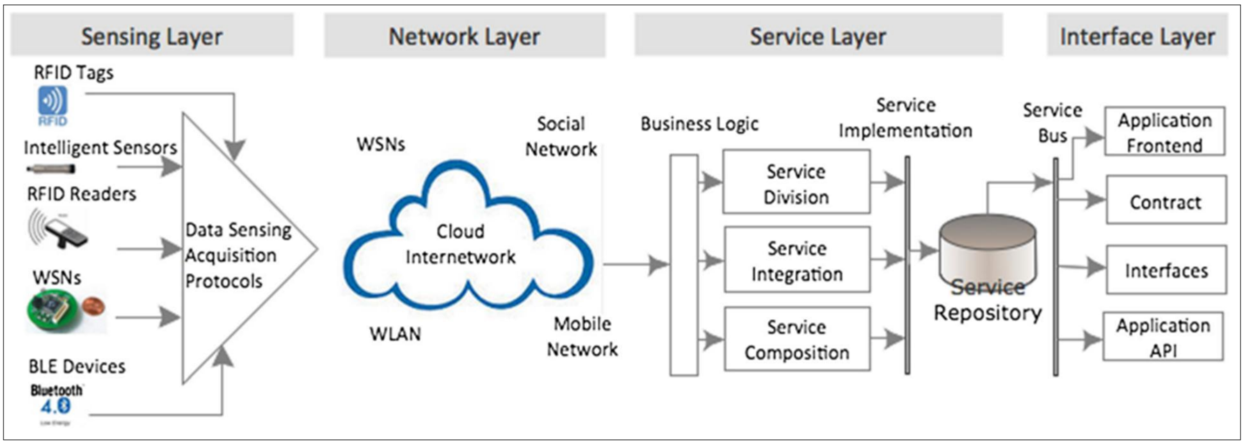

Figure 9: IoT architecture layer [38] .

Now from this understanding of the IoT principles the main particularities that IIoT possess can be summarized as follows:

- More requirements of real-time and reliable data, as industrial operations require greater levels of precision, therefore usage of more precise sensors.
- Commonly used as part of more complex systems along with technologies like cloud computing or big data. Thus a certain degree of interoperability with other operation technologies is required.
- Security issues should be further considered as disruptions may lead to great costs.

Cyber-Physical Systems

The concept of Cyber-Physical Systems can sometimes appear as exchangeable with IoT, in fact there is not a clear distinction between them as the origin of both concepts emerged from different communities, CPS from a system and control engineering perspective and IoT from a networking and information technology perspective [39] . For this work the concept of CPS would be more associated with the integration of computing capabilities with the physical components and the IoT concept will be more related to the connection of products with the internet.

CPS can be defined as the set of technologies that interconnect computational and physical capabilities; it embraces smart elements that communicate with each other and have the ability to perform intelligent tasks like controlling the needs of workpieces or altering the manufacturing strategies by themselves [33]. CPS systems consist on three parts according to [33]:

1. Communication, wired or wireless connects the CPS to a higher level such as control or lower-level like physical world components.
2. Computation and control, is where the intelligent commands are generated from the received measure.
3. Handling and monitoring components, in charge of the connection with the physical world, using actuators to handle physical components and sensors to monitor them.

There is a wide range of applications of Cyber-Physical Systems in the industry sector; authors in [40] list the practices with the highest potential for improvement in the industry sector, as the following table shows some of these applications grouped in categories of different industrial topics.

Category	Applications
Automatization	• The context awareness of smart machines allows for particular operations by accessing the information of each material or product. • Machine to machine communication optimizes the sequence in production steps based on previous determined algorithms. • Automated guided vehicles are able to transport components and working materials.
Autonomatization (Control and coordination of processes without human intervention)	• Upgrade of SCADA system that allows for condition monitoring and situation based system reconfiguration. • Facilitates cost-efficient production of mass-customized products. • Safety related benefits of absence of personal.
Human machine interaction	• Sensors permit the safe synchronous work between human and machine. • Human machine collaboration reduces the workload and lead to overall optimization. • Robotic exoskeletons enhance human weight lifting related activities. • Decision support systems supplies users with needed information to perform their work.

Decentralization	• Complex event processing can be performed in a leaner and faster way with decentralized computer solutions.
Digitization for Process Alignment	• Digitalization of warehouse and logistics enables self-organizing production to include real time inventory. • Automated e-procurement improves availability of parts and materials enhancing just-in-time production. • Remote maintenance, repair and operation. • Product lifecycle monitoring.
Knowledge Management	• The amount of real time information enables value creation in technical processes. • The staff practical knowledge should be recorded.

Table 2: CPS applications in industry

Cloud computing

Cloud computing (CC) have become widely implemented in the last years and each day more businesses are making use of this service, from industrial manufacturers to entertainment companies. The basic principle of this tool is to provide access to the user to computing resources and services without the need of owning and managing the entire software infrastructure.

A straight definition of the cloud that gathers the main ideas of the concept is the following:

> Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay per-use model in which guarantees are offered by the Infrastructure Provider by means of customized SLAs [41, p. 2].

CC platforms differ in certain features depending on the service they offer, however the majority of them share some common characteristics, [42] present the five essential characteristics that cloud platforms share and are shown in Table 3.

Characteristic	Description
On-demand self-service	Consumers can unilaterally provision computing capabilities as needed automatically without the need of human interaction with provider.
Broad network access	Capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous client platforms.
Resource pooling	The provider's computing resources are pooled to serve multiple consumers, with different physical and virtual resources dynamically assigned according to consumer demand.
Rapid elasticity	Capabilities can be elastically provisioned and released to scale rapidly with demand.
Measured service	Cloud systems automatically control and optimize the use of resources by leveraging a metering capability at some level of abstraction appropriate to the type of service

Table 3: Characteristics of CC platforms.

Cloud Computing platforms can be classified concerning the deployment model and the provided service model structures they offer [33], [42], [41]:

Deployment model

The model chosen will depend on the business's needs in terms of costs, data governance regulations and data confidentiality.

- *Private cloud.* The infrastructure is provisioned by a single organization and it offers special benefits for their users as it contains particular services for the organization.
- *Community cloud.* Offers exclusive use to a specific community of consumers of multi organizations that share concerns about the organization's infrastructure.
- *Public cloud.* Is provisioned for open use by the general public. Usually located in data centers.
- *Hybrid cloud.* The cloud is a composition of two or more distinct cloud infrastructures that remain unique entities, but are bound together by standardized or proprietary technology.

Service models

- *Infrastructure as a service* (IaaS). The consumer is provided with computer resources like processing or storage capacity, where users can deploy and run arbitrary software as operating systems applications.
- *Platform as a service (PaaS).* The capability provided to the consumer resides in the access to software platform where consumer-created or acquired applications run on. The consumer does not manage the cloud infrastructure, but control the deployment and configuration settings of the applications.
- *Software as a Service (SaaS).* Consumers are provided with access to applications running in the cloud via interfaces like web browsers or program interfaces. It allows for the elimination of service application on local devices gaining better performance efficiency. Enables software applications such as CAD and ERP to run with a lower total cost ownership.

Cloud manufacturing

In the context of the manufacturing industry, the term of cloud manufacturing refers to the integration of cloud computing technology into the processes of manufacturing. The main purpose of cloud manufacturing is to provide users access to services in all stages of product lifecycles, shifting manufacturing from product-oriented to service-oriented [33]. The manufacturing resources available in the platform can be physical resources (equipment, computers, servers, raw materials, etc.) or manufacturing capabilities (product design capability, simulation capability, maintenance capability, etc.).

Pay-as-you-go services, production scaling up and down per demand, and flexibility in deploying and customizing solutions are some of the possibilities that offer the implementation of cloud manufacturing [43].

Fog and Edge computing

In a predicted future IoT system where the number of connected devices and the data generated will exceed the network's capacity. The solution will require a development of the network's capacities by moving computing and storage capabilities to the edge of the network. This approach known as distributed intelligence will allow to handle the increasing volume of end devices by sending to the cloud center only the necessary information and by doing most of the processing at the remote site, it will also reduce delays and overloads in data transfer and will allow to run operations even when the access to the cloud center is not possible [44].

Fog and Edge computing are two similar often confused concepts that aim to bring cloud services and resources closer to the data generator devices. The main difference between the two is where their processing structures work, as fog computing works with the cloud, placing its computing intelligence at the local area network (LAN) whereas edge computing place it outside the cloud into edge nodes such as embedded automation controllers [45].

Big Data analytics

The exponential growth in data generation in todays connected world is expected to keep rising with the implementation of IoT and similar technologies. All these generated data holds a lot of value, however the process of sorting out the valuable information requires for adequate proceedings.

In this context appears the concept of "Big-Data" that can be often confused, as it not only refers to the definition of the particularities of a type of data, that is characterized by being high-volume, high-velocity and high-variety [46], but it also refers to the field that gather the technologies in charge of analyzing and dealing with this generated data.

The data usually comes from heterogeneous sources and in different formats of structured data (digits, symbols, tables…) or unstructured data (text, audio, video…). More particularly in manufacturing processes, according to [47] the data generated can be classified as:

- *Management data.* Collected from manufacturing information systems (e.g.. MES, ERP, CRM) including data related to product planning, material management, inventory management, sales and more management operations.
- *Equipment data*. Generated from the IIoT of the smart factories, including real-time performance, operating conditions or maintenance history of the equipment.
- *User data.* From ecommerce and social networking platforms, entailing user demographics, profiles, preferences and behavior.
- *Product data.* From smart products and product-service systems including product performance, context of use, environmental and user biological data.
- *Public data.* From governments, data related to intellectual property, civic infrastructure, scientific infrastructure and development, environmental protection and health care. For guaranteeing manufacturers with the compliment of the regulations and industry standards.

In order to extract valuable information from this generated data, it has to be stored, managed and then analyzed. The analytical process is where the real value is created and where organizations need to put the effort to develop efficient ways of working, to turn this great amount of data in valuable knowledge. This information can be translated in systematic guidance for production activities during entire product lifecycles, obtaining less faults and more savings during the production processes and helping managers in decision- making and problem solving related to operations [33].

Another great resource of Big-Data is Predictive analytics. This tool comprises a variety of techniques that predict future outcomes from current and historical data, allowing predictions in many different work fields from jet engines failures to consumer behaviors. Its basic idea is to uncover patterns and capture relationships in data using statistical methods [46].

Data-driven smart manufacturing is considered to be the process where enterprises utilize Big Data analytics to exploit the data from manufacturing to refine their processes, improving product efficiency and the performance of a product. Data driven smart manufacturing shares the following characteristics [47]:

1. Customer-centric product development focusing on customized product design enabled by the employment of users' data precisely quantified with Big Data analytics.
2. Self-organization of manufacturing resources and task data for smart production planning. Making use of both internal and external data from the manufacturing sites.
3. Self-execution from a variety of data from the manufacturing process for precise control. Raw materials and parts can be sent to any manufacturing site that requires them.
4. Self-regulation from real-state data for manufacturing process monitoring. Enables generation of automatic responses to unexpected events.
5. Self-learning and self-adaptation from historical and real-time data for proactive maintenance and quality control.

There are many existing applications of Big Data in manufacturing and others that are yet to be developed. The following are highlighted in [48] as some of the most valuable ones:

- Product design is shifted from experience and inspiration based to data and analysis-driven design. Users' behaviors and market trends translate consumer needs into new products.
- Smart production planning is conducted based on manufacturing resource data. The current availability and capacities condition the strategy.
- Real time data allows for optimal operational control strategies during the manufacturing process.

- Making use of the predictive ability of BD, health and fault monitoring are conducted for active preventive.

Simulation

Simulation is a key technology in the development and implementation of modern manufacturing. It allows to gain insight into complex systems, to develop and test new operating or resource policies before implementing them and also to gather information and knowledge without disturbing the manufactured system [49].

There are many existing methods and tools of simulation in the manufacturing context: Computer-Aided Design (CAD) a technology that assist in the creation, modification, analysis and optimization of a design, Enterprise Resource Planning (ERP) a system comprising software applications used to manage company-wide business processes and many more that work all along the product lifecycle. In the following paragraphs a deeper explanation of two simulation technologies is given, Digital twin (DT) and Augmented Reality (AR) as they are considered to be the new simulation modeling paradigms [33].

Digital Twin

Digital twin is a precise digital representation of a complex object that simulates the behavior of the real object to obtain valuable feedback information about the performance of the object along its entire lifecycle. It consists of three main parts: The physical product, the virtual product and the data that connect both.

The main features that characterize the implementation DT according to [50] are the following:

1. *Real time reflection.* Virtual space is the real reflection of the physical space allowing ultra-high synchronization and fidelity.
2. *Interaction and convergence.* In physical space as the data generated in various phases of the physical world can connect with each other. Between historical data and real-time data, not only depending on expert knowledge but also collecting data from all deployed systems real-timely. Between virtual and physical space with smooth channels that makes them interact easily.
3. *Self-evolution.* DT can update data in real time allowing for continuous improvements of the model.

The current main applications of digital twin are developed in the field of aeronautics and astronautics for failure prediction and product service maintenance. In [50] some of the potential applications to solve problems in PLM management are addressed in terms of: *Product design, Product Manufacturing* and *Product Service.*

Concerning *Product Design*, the implementation of DT technology enhance other strategies like Big Data and Cloud Computing design processes, as the first lacks in convergence between physical and virtual space and the latter fails in providing quick responses to real-time changes. Digital Twin design process can be divided into three phases: Conceptual design, detailed design and virtual verification.

- In conceptual design information such as consumer satisfaction, products sales, investment plans and many others have to be considered. Trough digital twin all this huge amount of scattered data can be integrated in a physical model for a better understanding and allowing for a better communication between clients and designers.
- Detailed design requires for repeated simulation tests, DT solves the problem of not having real-time and environmental-impacted data as it exists and evolve during the lifecycle of the physical object recording all data of the product and the influence on the environment.
- Virtual verification removes the need of small batch productions after the product design as it allows for prediction of accessories' quality by predicting their behavior in the DT, by making full use of data of equipment, environment, materials… and allowing for a faster and convenient redesign process.

Digital twin-driven *Product Manufacturing* solves the existing problems in the shop floor of lack of optimization in resource management capacity, the divergence between production plan and actual production and the inaccuracy in manufacturing process control.

A Digital Twin Shop Floor is composed of: Physical Shop Floor (PS) a group of production assets in charge of receiving production tasks and orders and executing them, Virtual Shop Floor (VS) as an ultra-high-fidelity representation of PS that carry out simulations and forecasts for production plans and processes and monitors the production in real-time, Shop Floor Service System (SSS) which consists on the services providing support to the manufacturing processes by taking optimization orders from VS and finally Shop Floor Digital Twin Data (SDTD) that refers to all the generated data and the data fusion of all the three previous components.

The digital twin-driven *Product Service* is intend to solve the current problems in maintenance statistical methodologies based on the assumption of similarity between the environment in which the product operates and the circumstances in which the statistical methodologies are constructed, leading to a reactive approach based on heuristic experience and worst-case scenarios.

In the DT methodology degradation and anomalous events can be understood and unknowns can be foreseen previously. In this context [50] mention the following nine categories of services that DT can provide to product users and manufacturers:

1. Service of real-time state monitoring.
2. Service of energy consumption analysis and forecast.
3. Service of user management and behavior analysis.
4. Service of user operation guide.
5. Service of intelligent optimization and update.
6. Service of product failure analysis and prediction.
7. Service of product maintenance strategy.
8. Service of product virtual maintenance.
9. Service of product virtual operation.

Augmented Reality

Augmented reality is a fast growing emergent technology which future applications are meant to work in many different sectors like entertainment, marketing, surgery, manufacturing and so forth.

The working principle of augmented reality technology is to create an enhanced/augmented view of the physical world by adding virtual generated information that enables the user to access valuable data while interacting with the physical object. AR systems require for precise computation and real-time tracking, since synchronization between the real and the virtual world must be performed with enough speed, for that purpose the system has to be hardware and software intensive [51]. The main hardware devices that AR systems need according to [51] are the following:

- *Display devices* in charge of projecting the combined virtual and real world scene to the user. These devices come in different formats: Head-mounted display devices have been applied widely in AR applications, however, due to its discomfort in use they are becoming obsolete [51]. Handheld devices, specially designed for the applications or commercially available like mobile phone devices and Spatial Projectors that allow the user to directly see the virtual information displayed in the physical world.

- *User tracking* is an essential part of the system as it is critical in the accuracy of the applications of AR. There are many different techniques (vision based, inertia based, GPS…) applied depending on the environment the application is being used. A method that has been recently been explored is the computer based vision combined with sensor tracking technology, particularly Ratio Frequency (RF). This method tracks the position of the RF modules with the use of an RF reader.
- *Haptic and force feedback* enhance the immersive and interactive sensation for the user.

Regarding the software systems the effort is being putted in the development of algorithms that allows for the tracking and registration issues, in this context some open source applications and libraries have been developed (ARTag, ARToolKit, PTAM…) that use different working principles for the tracking process.

The use of Augmented Reality on manufacturing processes as a simulation tool assistant has been proven to be efficient for problem solving, as it increases reality operator's perception by introducing "artificial" information about the environment displayed with the real object [33].

There are many fields of applications in the manufacturing context, some of them are still in an experimental phase and others are currently being implemented. The authors in [51] outlined some studied applications in the fields of robotics, factory layout planning (FLP), assisted maintenance, CNC simulations and assembly design and operations. Other relevant tasks considered by [33] in the creation of value with AR technologies in the industrial and manufacturing environment are shown in Figure 10

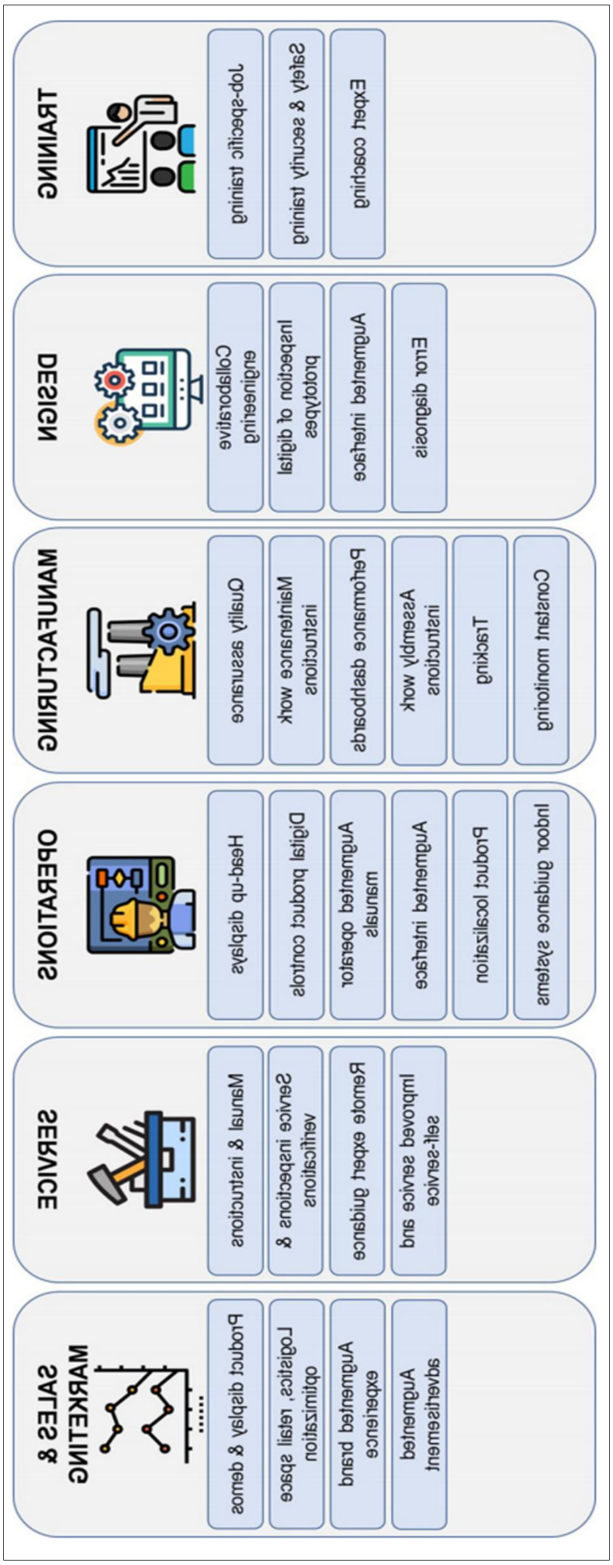

Figure 10: Augmented Reality applications [33]

Additive Manufacturing

Additive Manufacturing (AM), also known as 3D printing has been in the last decade one of the most resounding topics in the manufacturing and industry context gathering also considerable popularity among the stream media. It is considered to play a crucial role in the transformation of the industry as it is intended to replace many of the conventional manufacturing processes; the substantial technological developments that AM has been trough in the last years are revealing its true potential, bringing into industry high feasible applications [33].

Additive Manufacturing became possible by the previous development of technologies like computer-aided design (CAD), computer-aided manufacturing (CAM), and computer numerical control (CNC) [52]. The basic principle of AM is to manufacture 'objects' from a digitalized model by depositing the correspondent material in a layer-by-layer or drop-by-drop manner using digitally controlled and operated tools.

According to [53] some of the potential benefits that AM brings to the manufacturing processes are:

- A direct translation of design to component that leads to a great reduction in overall product development and manufacturing time.
- Enables a greater customization of the product and the availability to manufacture components to their final or near final shape with minimal or no additional processes.
- Functional design allowing complex internal features and flexible and lightweight components, confer the possibility of manufacturing hollow or lattice structures.
- Potential approach to zero waste manufacturing by efficient material utilization and smaller operational foot-print towards manufacturing a large variety of parts.
- On demand manufacturing and excellent scalability.

Along with the manufacturing potential benefits that AM can offer, it is worth to mention the concepts of Inspection and Quality Assurance, as they are considered to be corner stones in the manufacturing paradigm. In this context the counterpart of the complex piece manufacturing of AM is the lack of a robust quality assurance scheme due to the lack of appropriate measuring tools [44]. Proper metrology techniques is a must for a market that demands adequate and standardized measures to ascertain functional properties, shape and dimensional tolerance; metrology is equally important for optimizing and reducing the operational costs as it improves the utilization of materials, increase production yield, reduces part rejection and increase energy efficiency [44].

Regarding the manufacturing operations of AM, there are different existing working processes of additive manufacturing intended for different materials and applications; The *International Organization for Standardization (ISO)/American Society for Testing* and *Materials (ASTM) 52900:2015* standard classify standard Additive Manufacturing processes into seven categories, furthermore within these categories exist different working procedures and techniques intended for different AM machines, but, it is considered to be out of the scope for the following explanation :

1. *Binder Jetting (BJ):* This process is mainly characterized by the absence of heating, avoiding residual stresses [54]. In this process a thin layer of powder is glued together using a liquid adhesive spray in the parts specified by the CAD file.
2. *Directed Energy Deposition (DED):* Usually conceived for the usage of metal wire or powder; high energy heating sources (normally laser beams) merge into the material injector generating the object.
3. *Material Extrusion (ME):* Is becoming one of the most prominent additive manufacturing processes [54]. The objects are generated by depositing an extruded material layer by layer; normally a thermoplastic filament that is melted and deposited in horizontal or vertical direction.
4. *Material Jetting (MJ):* Works as a two dimensional ink jet printer, the material is jetted into a platform where it solidifies and the model is built layer by layer.
5. *Powder Bed Fusion (PBF):* Similar to BJ but in this case the fusion of the powder is fused together using a heat source such a laser or an electron beam (for metal powder).
6. *Sheet Lamination (SL):* In this process sheets of materials are bonded together using adhesives (Laminated object manufacturing) or a heat source (Ultrasonic additive manufacturing) to form the 3D object.
7. *Vat Photopolymerization (VP):* Also known as Stereolithography is one of the first and most widely used method of 3D printing; is a liquid based process that cures a photosensitive polymer when a laser beam contacts the resin [52].

The Table 4 shows for each of the above mentioned AM processes some of the main advantages and disadvantages identified by the authors in [54] and [53], along with the suitable and commonly used materials according to [53] and the main applications of each process considered by [54].

Type	Advantages	Disadvantages	Materials	Applications
BJ	• Free of support • Design freedom • Large build volume • Low cost	• Fragile parts with limited mechanical properties • May require post processing	• Polymers • Ceramics • Composites • Metals • Hybrid	• Prototyping • Tooling
DED	• High degree control of grain structure • High quality parts • Can operate in open air	• Surface quality dependent on speed • Limited to metals/ metal based hybrids	• Metals • Hybrids	• Repair/build up large volume pieces
ME	• Economic • Scalable • Fully functional parts • Good structural properties	• Vertical anisotropy • Slow building times • Low quality may require post processing	• Polymers • Composites	• Prototyping • Tooling • Office manufacturing.
MJ	• High accuracy of droplet deposition • Low waste • Multiple material parts • Multicolor	• Support materials often required • Parts may have low strength and durability	• Polymers • Ceramics • Composites • Hybrid • Biological	• Electronics • Consumer products • Tooling • High resolution prototypes
PBF	• Low waste • Relatively inexpensive • Wide range of materials • Powder bed act as support	• Lack of structural integrity • High power required • Size limitations	• Polymers • Ceramics • Composites • Metals • Hybrid	• Aerospace • Automotive • Medical products • Tooling • Dental implants
SL	• Low cost	• Strength and integrity of	• Polymers	• Tooling

	• High speed • Ease material handling • Allows combination of materials	parts depend on adhesive • May require post-processing • Difficulties with complex geometries	• Ceramics • Metals • Hybrid	• Large pieces
VP	• Large parts • Excellent accuracy • Excellent surface finishing	• Limited to photopolymers • Low durability • Expensive precursors • Slow	• Polymers • Ceramics	• Prototyping • Consumer toys • Electronics • Guides • Fixtures

Table 4: Characteristics of the different AM processes.

Looking at the actual and potential applications of AM, it can be observed that they are present in the majority of the industry sectors and currently in Europe contribute to 1.6 million jobs and 11% of the EU production [53]. From all the different possible applications of AM the authors in [52] consider the following as the most remarkable ones:

- *Lightweight Machines*. AM as mentioned before allows for the possibility of manufacturing light weight pieces, which is of great interest for the automotive and aerospace industries that are always looking for lightness in their products.
- *Architecture modelling*. The creation of models in architecture is a very important and difficult task, when the model entails complex structures AM is an adequate tool.
- *Medical applications*. The medical world is considered to be one of the most promising ones for AM. As it allows for a high quality and rapid prototyping of bone transplants and models of damaged bones for better analysis of patients' diagnosis, also better and more adapted prosthesis can be created as the designs are more adapted to each patient. AM has as well great potential in dentist application as the model of a patient's mouth can be easily build.
- *Manufacturing cell fuels*. This particular technology requires for a very precise deposit of a thin film, a requirement that AM can properly perform.
- *Art and user services*. AM becomes an interesting tool for artists to elaborate complex forms involving fashion, furniture or lighting among others. The low acquisition cost

of some printers open up opportunities for particulars and non- manufacturing institutions such as schools or universities to benefit for the possibilities of AM.

Additive Manufacturing is not intended, at least in the near future, to replace mass manufacturing; indeed is more suitable for high value low volume products due to its ability to produce shapes and complex products which are not possible or cost-effective for conventional manufacturing processes. Also, AM is not tied to traditional economies of scale or unit labor costs and the replacement of the whole value chain of the products will mean a compression of all the processes of the value chain which will require in-house expertise in materials, metrology, assembly… a knowledge that is normally widespread into many different actors along the value chain [53].

A study conducted among industry experts and researchers about their view of Additive Manufacturing processes in the year 2030 [55], makes a great emphasis in the change of the production system that could be generated regarding spare parts, as the production of spare parts with AM will simplify logistics reducing time expenditure and will also reduce the spare parts stocks. The study also highlights the possibilities of multi-material products that AM will enable and the importance that AM will acquire in a future where products will always remain in continuous modifications and upgrades.

Perceived challenges for Industry 4.0 implementation

Industry 4.0 is still on its development phase, some of the technologies are grounded and functional others are still being developed to be commercially available, but more importantly its degree of implementation in industrial companies is still weak. Through the following chapters some of the challenges that Industry 4.0 implementation faces are presented and analyzed.

The challenges for SMEs

Companies that want to introduce 4IR technologies in their businesses need to face certain technical and economic challenges. Nevertheless as a research conducted among German companies [56] states, companies are willing to face digitalization despite these challenges in which enterprise size plays an important role.

SMEs have great importance on the industrial sector, particularly in Europe; moreover they are a crucial factor in the supply chain of big companies. Some of these big companies are already transitioning towards Industry 4.0, however SMEs are experimenting more difficulties in embracing this transition. There is a need of closing the gap between the development of the transformation between big companies and SMEs in order to accelerate the process of transition.

Investment requirements are one of the main challenges that SMEs face in the adoption of a 4IR system, the required infrastructure demands a considerable initial investment. Despite the fact that the adoption of these new technologies will entail economic benefits for companies, the price of the deployment of these new technologies is still high and a total transformation of the entire production process can have tremendous costs.

Other challenge that particularly affects SMEs is the difficulties they face when it comes to change from the old to the new systems. These companies normally have lack of expertise in these new technologies and they have to turn to third parties. Also businesses rooted in traditional practices may have a lack of willingness to transform their way of working, slowing down the transition.

Cybersecurity

A fully digitalized system in which every working piece is connected and stores valuable information holds the risk of being exposed to cyber-attacks that can compromise the security in different areas of the company.

The supply chain is one of the key areas of the company as it records sensitive information from a considerable number of participants. A digital supply chain should be properly balanced in terms of the transparency that it entails in terms of sharing data from different stakeholders and maintaining security for other information that can have privacy risks. Organizations need to consider which data is available, however providing access to certain data can facilitate gaining access to other valuable information for those with malicious intentions [57].

Smart factories rely on a digital infrastructure the performance of all their processes, these infrastructures are supported by commercial software products which introduce a variety of exposure points that can endanger the performance of the system. A cyber-attack that shuts down the production processes of a factory can result in considerable money losses, but the main issue with cyber-attacks is when they affect systems that are in charge of managing the safety of operators [33].

Smart products represent also considerable risks in terms of cybersecurity as they can generate threats even out of the production process. Once the product gets to the customer's hand the security of connected products cannot be guaranteed as it normally depends on the customer to update security settings or device firmware [57].

The issue of cybersecurity should be addressed in order to effectively transition to Industry 4.0 as its one of the main concerns of companies willing to embrace the transformation. The authors in [57] suggest three main approaches in order to address the problem:

1. Security. Stakeholders need to be certain about which of their vulnerable infrastructures are secure and which aren't by taking a measured risk-based approach.
2. Vigilant. A continuous monitoring of the systems is required to avoid possible threats. Real-time intelligence and AI are required to understand and predict harmful actions.
3. Resiliency. If an attack occurs how the system responds and how quickly the effects are remediated is of great importance.

Energy efficiency

Despite the fact that these new technologies will help with the accomplishment of a more energy-efficient and sustainable industry. The massive amount of devices that could be operating in IoT systems in a near future will have a considerable impact in energy consumption.

Connected devices with RFID technologies have very low energy consumption levels, however IoT systems can involve a great amount of devices with sensing, processing and communication capabilities that combined can consume a significant amount of energy.

Particularly are the wireless sensor networks the ones that have the greatest energy consumption rates [58]. The real impact of this energy consumption will depend of the magnitude of the system that in terms of involved devices, a number that is expected to exponentially increment with Industry 4.0.

However the authors in [58] explained how the magnitude of this problem can be tackled with the introduction of an energy efficient architecture. They proposed an architecture that as general overview reduces the energy consumption of IoT systems by reducing the time that the sensing devices are communicating with the use of a control layer that enables the communication just when is required.

Additive Manufacturing as explained before reports many benefits in the production processes as the reduction of time and operations which is translated in an overall reduction of energy consumption. However the production process itself of AM has a considerable rate of energy consumption, which in some cases could be bigger than the one used in traditional manufacturing processes.

Connecting Circular Economy and Industry 4.0

In the last years the topics of Circular Economy and Industry 4.0 have been addressed from many different points of view, the synergy between the two is a topic that has recently drawn the attention of academia, however due to the scarcity of research papers and industrial applications, is still considered to be in its early phases of development.

The wide extent of these two terms difficult the establishment of a specific framework of interrelation, as the synergies between CE and 4IR technologies can take place in multiple areas and the degree and the form of interrelation will certainly depend on the particular applications they are intended for. Nevertheless, in this section the relationship between both terms will be explored, first by presenting the existing literature that analyzes the topic in a more conceptual and broad manner, then the topic would be addressed in a more particular way with the introduction of a series of industrial and academic case studies that provide a more realistic view of the challenges and opportunities that arise with the implementation of this two strategies in various industrial sectors.

Conceptual framework of the Digital Circular Economy

It is reasonable to think that some of the main principles of CE: Dematerialization, share of assets or product multifunctionality; will certainly be enhanced by business practices based in the use of digital technologies, as they encourage these product capabilities. Nevertheless, the benefits that the merge of this two value propositions can generate are not always that obvious, and in some cases involve a combination of different 4IR technologies along entire supply chains and trough whole product lifecycles. The diversity of these possible combinations is far-reaching, thus, through this chapter only some of the most discussed possibilities will be presented.

As mentioned before the conceptual framework of the symbiosis of 4IR and CE is not a straight forward concept, hence in the existing literature the given approaches differ considerably. In the following paragraphs several studies will be reviewed in order to outline the most relevant conclusions of the academia.

Opportunities of 4IR technologies to promote Circular Economy

In a recent book that has the intention to address the challenges and opportunities for the implementation of a global circular economy system [59]. The authors identified the main capabilities of 4IR technologies that enable businesses to decouple production and growth from consumption of natural resources: First, technology developments which implies greater efficiencies in all stages of the product lifecycle and allows for less overall resource and energy consumption, second 4IR technologies help to drive innovation as new entrants will disrupt the existing market forcing companies to turn into new business models. Finally, the implementation of these technologies will increase information transparency through the gathering and analysis of data, allowing companies to access new levels of visibility of the production processes, a greater degree of connectivity trough the supply chain and an upgrade in production flexibility.

A recent report that evaluates the opportunities that digital technologies can bring to the implementation of a Circular Economy system [60], indicates that digitalization is designed to address complexities thus is optimal to deal with the challenges that arise with the shift to a CE system. However, [60] also points out that digitalization if not properly managed holds the risk of ending up in unwanted rebound effects, such as the reinforcement of an unsustainable linear take make-dispose economy. The report stablishes three categories in which the different approaches for using digitalization in the transition to a CE can be divided Figure 11:

1. *Improve knowledge, connections and information sharing*. A better management of data that enhance information sharing and knowledge could raise awareness and improve policymaking. Also digitally-enabled solutions facilitate the connections of stakeholders and improve traceability along the value chain.
2. *Make business models, products and processes more circular*. The better management of data and the implementation of digital enabled solutions could contribute to greater circularity supporting more sustainable models and improving circularity activities.
3. *Strengthen the role of citizens and consumers*. Digitalization can be used to inform, educate and influence people. Converting them into active participants in the data economy and co-creators of knowledge.

Other area in which Industry 4.0 can have a great impact is the previously mentioned issue of measuring circularity. The traceability that introduces 4IR in the systems is a perfect feature for creating adequate tools for measuring at circularity. In an ideal system where everything is measured, traced and recorded the progress in CE implementation is much easy achievable and as consequence the correspondent actions are more aligned with the progress.

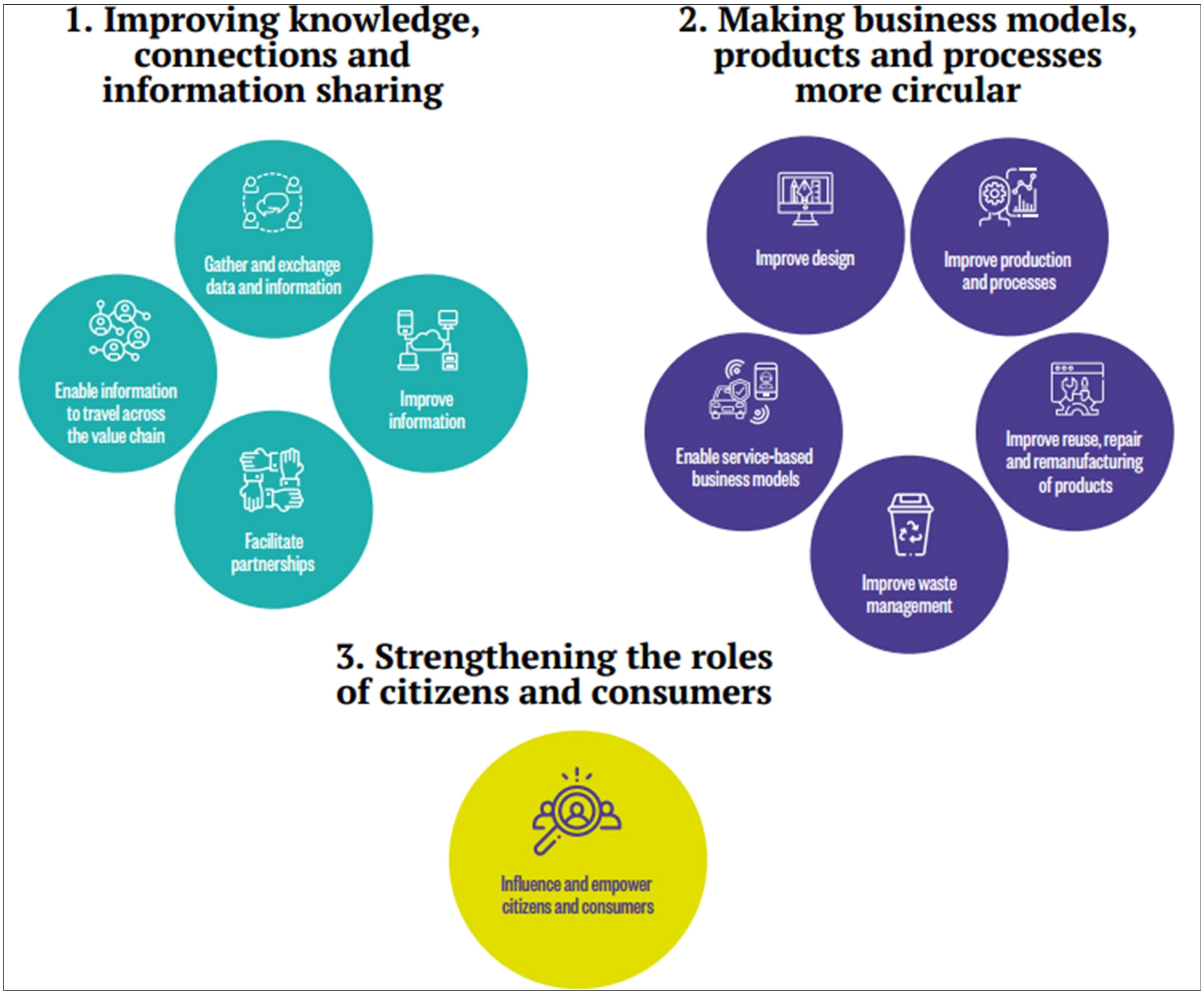

Figure 11: Digitalization in the transition to a CE [60].

Circular Economy and Intelligent assets interaction as opportunity creators

From a broad vision about the synergies between CE and digital technologies, an Ellen McArthur report [61] studies the relationship between the key value drivers from both Circular Economy and Intelligent assets. Referring to Intelligent assets as physical objects with the ability to communicate and transmit information about themselves and their surroundings mainly based on IoT technologies.

The Circular Economy value drivers defined by [61] as key for generation asset and resource productivity are the following: Extending the use cycle, increasing the utilization, looping through additional use cycles and regeneration of natural capital. The core ideas of these value drivers have already been addressed through the paper in previous chapters, so in order to avoid repetitive information the definitions of these value drivers are provided in the Appendix 2.

On the other hand, Intelligent Assets according to [61] can supply three types of knowledge about assets that serve as the main forms of value creation for business practices:

- Knowledge of the location. Trough tracking systems assets can be located. Asset location has significant advantages for sharing models, it also represent a great opportunity to reduce costs of logistics and enhances a more efficient use of resources. Location knowledge is of particular importance for business with mobile assets and it also helps with auditing process for companies.
- Knowledge of the condition. The information that sensors and similar devices provide about the status and performance of the asset enables predictive maintenance, repair activities or information about recommended changes in use patterns. It also allows for product use analysis, material composition and potential change of product functions.
- Knowledge of availability. Mainly indicates if the asset is idle, but also provides information about supply/demand dynamics of assets, which allows for the development of sharing models and service based business models. Knowledge about availability also includes information about asset ownership and if it involves energy systems it can provide information about usage and demand of energy in a certain location and time frame.

The interplay of these value drivers can generate new opportunities for value creation. To illustrate these interactions [61] presents a matrix Table 5 with examples of opportunities to implement this interrelation between value drivers.

	Intelligent asset value drivers		
Circular Economy value drivers	Knowledge of location	Knowledge of condition	Knowledge of availability
Extending use cycle length	• Guided service for component replacement. • Optimised route planning to avoid	• Predictive maintenance and replacement of falling components prior to asset failure	• Improved product design from granular usage information • Optimized sizing, supply, and

	vehicle wear	• Change use patterns to minimize wear	maintenance in energy systems from detailed use patterns
Increasing utilization	• Route planning reduces driving time and improves utilization rate • Swift localization of shared assets	• Downtime minimization trough predictive maintenance • Precise use of input factors	• Automated connection of available, shared asset with next user • Transparency of available space (e.g. parking) to reduce waste (e.g. congestion)
Looping trough additional use cycles	• Enhanced reverse logistic planning • Automated localization of durable goods and materials on secondary markets	• Predictive and effective remanufacturing • Accurate asset valuation by comparison with other assets • Accurate decision-making for future loops	• Improved recovery and reuse/repurposing of assets that are no longer in use • Digital marketplace for locally supplied secondary materials
Regeneration of natural capital	• Automated distribution system of biological nutrients • Automated location tracking of natural capital	• Immediate identification of signs of land degradation • Automated ecosystem condition assessment	

Table 5: Interaction matrix of CE and Intelligent assets value drivers [61]

Impact of Industry 4.0 value drivers for sustainable and circular manufacturing

A McKinsey report about how manufacturing companies should navigate the implementation of Industry 4.0 technologies [62], establish a series of value drivers that have significant impact on the economic behavior of a typical manufacturing company, also the report links these value drivers with Industry 4.0 levers that enhance their performance.

In the following paragraphs as presented in [63], some of the previous value drivers will be analyzed in terms of their potential to encourage sustainable manufacturing applications for the accomplishment of Circular Economy business models with the use of Industry 4.0 technologies.

Using resources and optimizing processes. The interconnection of machines products and humans trough IoT and CPS enables to react in a very fast, efficient and automated way to every circumstance during production. The increase in traceability allows for a greater transparency in the consumption of resources, therefore a better assessment of the amount of resources needed for each production step can be performed and the whole process optimized. “Smart Materials” based on RFID or similar technologies will enable to trace materials through all the product lifecycle. The location of the materials will encourage the reduction of waste and the recovery practices especially of scarce resources. Furthermore, production processes can be optimized in regards of time, saving time and energy.

Utilization of assets. An “intelligent” asset equipped with sensor actuator technology provides information about its location, condition and availability. This is of great importance especially for businesses that have mobile assets, in addition, is an important facilitator of sharing models. The collection of data about the assets’ conditions will promote predictive maintenance and similar activities that extends the use phase and facilitates the application of manufacturing equipment in a new use phase.

Management of inventories. 4IR technologies provide real time data about stock levels reducing waiting times, inventory costs and storage space. This optimization entails apart from economic, sustainable benefits as too much inventory leads to great capital costs apart from unused and excess resources. Also, reduction of inventory levels leads to decrease in energy needs for proper storage of the inventory as well as less waste by materials turning old or outdated.

Quality improvement. Real time problem solving, advanced process control or real-time error corrections hide potential for sustainable manufacturing trough quality improvement. Manufacturing sequences are designed more resource-efficiently reducing the consumption of materials and energy. Also the increase in quality will reduce the need for rework processes and the waste will certainly be reduced during the production process. Furthermore, products of higher quality will be able to be kept much longer on the operational phase extending the product lifecycle.

Reducing time to market. Faster and cheaper R&D processes mainly through the use of AM technologies. AM allows for the manufacture of final prototypes without the need of a trial error procedure, reducing the total amount of material needed and the probability of creating defective products. Furthermore, AM reduces the total amount of material needed and allows for the creation of more customized products.

Match of supply and demand. More accurate demand planning will lead to reductions in waste, input materials are better projected and overproduction is reduced. Consequently transportation of raw material is reduced in the supply chain entailing energy savings. Reuse and preparation of already used materials can be planned more precisely and companies can cover they demand by cycling used materials and reuse and recover products.

Service and aftersales. New business models will emerge with 4IR technologies that will bring the manufacturer or service provider closer to the customer. Products will be leased or borrowed instead of being bought providing more importance to the service and aftersales operations. This will encourage maintenance and repair activities keeping the operational phase of the product for longer time, it also becomes easier for the provider to get back products and parts after the use phase as they can be traced over the whole lifecycle and in consequence products are more easily recycled, reused or remanufactured by the provider that extends the responsibility over the product to the whole lifecycle.

In which CE area has Industry 4.0 technologies more potential?

In this section the CE areas in which each particular technology has more influence will be analyzed. For that purpose an examination of a recent literature review [64], which analyzes the connection between a set of Industry 4.0 technologies with some CE selected topics is performed. The literature review stablishes the connections by searching in the reviewed articles where the selected terms appear, how often and in which context. The main findings about the correlation of each selected technology with a CE topic are the following:

- Additive manufacturing. AM is the technology with the most appearances in papers relating CE and 4IR. Most of the relations described how AM can support the lifecycle management of product and processes. Also some scholars discussed how

AM can upgrade current recycling processes, promote reuse/remanufacture or make use of biomaterials.

- BigData and analytics. In contrast with AM it has been considered less frequently by experts. BDA is considered to be the easiest way to digitalize the CE. Other considered applications are: Develop automated approaches assessing potential value pathways for secondary materials, develop tools, procedures, open data and services for promoting: reuse, assess innovative business models, manage lifecycle data or implement smart manufacturing practices.
- Cyber-physical-systems. Were the less discussed ones. They are mainly related with lifecycle management of products and with the development of new services, especially for maintenance reasons. In few cases were related with remanufacturing practices or multi-agent systems for managing the extraction of natural resources.
- Internet of Things. Considered with AM one of the most important technologies that support Circular Economy practices. Apart from papers that focused on the potential use of IoT in extending the information exchange along the product lifecycle. IoT was considered to have many other applications to support CE. It can support strategies for the waste management in cities or connect stakeholders across the value chain. Also it promotes the digitalization of CE practices by implementing smart industrial environments dynamic feedback loops or the creation of new service models or services.
- Simulation. Most of the papers addressed the relation between circular business models and lifecycle management with simulation tools. Other discussed topic is the supply change management where simulation could optimize the performance through probabilistic neural networks or modelling of the material flows. Simulation can enhance remanufacturing processes with the use of decision-support tools and the efficiency in exploiting natural resources trough eco-efficiency indexes.

The authors in [64] also analyzed the relation between 4IR technologies and CE by identifying which are the technologies that better fits or have more potential in certain CE-related areas.

AM, BDA and IoT were the most frequently described technologies for the digitalization of the CE. When it comes to support innovative lifecycle management strategies CPS is the term with more appearances followed by AM, IoT and simulation. BDA is the most related with new forms of disassembly and AM is suitable for new types of reuse and recycling processes and remanufacture along with Simulation. Efficient exploitation of resources is mainly related with IoT and BDA. The development of circular business models and new services can be associated with all of the technologies except from AM. Finally when it comes to the management of complex processes and supply chains simulation and IoT appear as the most mentioned.

Case studies

In this section some selected case studies will be presented, the cases are aimed to represent how Industry 4.0 technologies are used in both real and academic cases, in which sustainable practices encouraged by Circular Economy strategies are generated intentionally or as consequence of the technological applications.

The studied examples are selected from three of the industry sectors that are considered by the *European Circular Economy Action Plan of 2020* [65] as priorities in the application of Circular Economy measures along their supply chains. The industry sectors will first be shortly described addressing the main challenges they face in meeting sustainable requirements, then the case studies will be presented.

Resource efficiency in the textile industry

The actual society in developed countries is surrounded by rapid changing trends in many aspects of people's lives, from new music rhythms to fresh exotic dishes; the world of clothing and textiles is probably the most influenced in this matter as it is exposed to the introduction of new fashion styles constantly, changing the way people dress quite rapidly. This ends up with an over consumption of clothes, as people are buying more items and keeping them for a shorter period of time even though they are still in their useful life.

The textile industry is considered as one of the most resource intensive industries only after food, housing and transport [65]. The current linear system is strongly reliant on virgin materials from non-renewable sources, the choice of material is considered as one of the most relevant factors to determine the impact that the clothes have on the environment; from cultivation (land, fertilizer, water use…) to processing (energy, chemical and water use…) [59]. Conventional cotton that along with polyester are the most used materials in the textile industry, consumes significant amount of inputs in its production process, in fact, the manufacture of a single T-shirt and pair of jeans requires for almost 20,000 liters of water [59].

Human resources are also a great malfunction part of this industry, the low margins and the rapid changes in market trends have led to delocalized manufacturing activities in developing countries where the salaries are lower and the total investment of the textile companies in the manufacturing processes are substantially reduced. This have sometimes degenerated in companies involved with exploitive labor practices [66].

The sector is evolving into more sustainable businesses models, many fashion brands are implementing eco-design principles working in the creation of products that can be recycled, reused or biodegraded, however all this added value is lost in the system as the infrastructure and the processes of the recovery sector are not developed enough to accomplish these operations [66].

The actual recycling processes of conventional textiles are not efficient enough to properly manage the amount of disposed clothes generated; also the majority of countries have not yet developed a proper collection system in their municipalities able to handle the textile waste, as they have with standard municipal waste. As a result of these challenges, the disposed clothes are not adequately collected ending up in landfill or as a form of energy recovery and when properly sorted the profitability of the system is lowered due to the low efficiencies of the recycling processes. In fact, in the European Countries 73% of all the clothes (5.8 tons annually) that reaches their end-of life end up being landfilled.

Innovative ideas are required in order to transform the textile industry and 4IR technologies appear as great tools for doing so, as the following paragraphs demonstrate.

CircularID initiative

The company EON has developed a project that aims to solve the challenges of the implementation of circular practices in the fashion sector by connecting the products with IoT technologies. The aim is to create a protocol for product identification in which the manufactured garments are identified and characterized all along their lifecycle.

Currently there are some existing companies that are recovering and recycling textile products enhancing circular economy practices, however some challenges arise in these practices. The sorting process is normally performed by hand relying on the information presented in a label that can sometimes have a lack of information or even may no longer be attached to the product. If high volumes of textiles are meant to be collected a better scalable recognition system is needed to move goods in a faster way through the supply chain.

Also, another great challenge when it comes to textile recycling is the difficulty of separation of the blend of materials that exist in the garments, the new promising solutions that are able to properly recycle these products require for a precise quantification of the material input to the process, which again requires for a better process of material recognition.

The CircularID protocols will be able to provide the necessary specifications for each item validating its true content and aiding the sorting process by recognizing the product category and material content of collected textiles. The process of sorting will speed up and the possibilities for recovery practices will be enhanced.

When recovered products are put again into the market the information about the "new" product is not accessible, CircularID will facilitate brands the process of reselling their items as the product information could be easily accessed and provided to the customers.

How does CircularID works?

The connected product is digitally identified and connected to its characteristic data through IoT parameters. To link the physical product to IoT a digital identifier (RFID, QR, NFC…) is attached and the digital profile is accessed through interactions with the identifiers bias appropriate lectors.

The digital representation of the connected product as shown in Figure 12 will consist on the following components:

- *Digital birth certificate.* Is created for the finished product and includes data fields that as the product brand, name, color, material content and factory identification number among others.
- *Digital passport.* It includes the record of interactions of the product through its lifecycle, the interactions occur when the product identifier is read by an appropriate device. The passport serves as valuable tool for stakeholders to capture the valuable insights of the product usage, durability and movement in the value chain.
- *Identifier.* Consists on the physical device in charge of connecting the product with its digital profile. The identifier must remain attached to the garments along all its lifecycle to allow for access, verification and expansion of the digital information contained on the product. RFID, NFC, QR or UPC are the main examples of usable identifiers that should always be designed to remain intact for the full lifetime of the product.

The introduction of the CircularID protocol will entail a considerable number of benefits among the textile industry stakeholders as the ones appearing in Table 1, which are mainly due to the two primary functions enabled by the CircularID protocol: Identification of products that allows for a continued identification and monetization of the product trough circular business models and identification of materials that enables a better performance of the recovery activities mainly disassembly and recycling processes.

Figure 12: CircularID connected product components [66]

Stakeholder group	Roles	Impact & Value of CircularID™ Protocol for Targeted User Groups
Circulators	Collectors, Sorters, Resellers, Renters, Peer-to-Peer reselling, Repairer, Digital Wardrobe	• Enables transactions • Identifies products and materials for reverse logistics, collections and sorting • Enables efficient economy and marketplace • Creates economic viability • Communicates embedded value • Captures maximum value of products • Improves sorting efficiencies
Regenerators	Recyclers (includes ALL types of recyclers)	• Captures maximum value of materials • Provides accurate data and specification about materials to inform disassembly and recycling • Unlocks possibility for materials to meet unique technology specifications • Improves sorting efficiencies
Product Owner	Brands, Retailers	• Creates economic viability and visibility • Creates opportunity for ongoing revenue from existing product • Builds circular brand integrity and equity • Unlocks transparency across the product lifecycle • Creates the ability to share, exchange and access data with circular economy partners • Facilitates measurement of circular economy goals
Customer	Individual who uses product	• Helps customers maximize the use and value of product • Helps customers make intelligent decisions about purchases • Enables ease of sustainable quality and narrative • Allows customers to connect with brands after purchase to build more meaningful connections.

Table 6: CircularID Protocol value creation among stakeholders [66].

Modeclix

Modeclix is a patented innovative way of applying additive manufacturing to the textile industry developed in the *University of Hertfordshire*, UK. The model is based on printing a flexible material that is able to create a great variety of shapes and structures perfect for clothing. The main innovation that characterizes this process is the ability to be infinitely deconstructed and then reconstructed by hand after the material is printed.

The AM process has been successfully tested using the Selective Laser Sintering technique and employing white Nylon powder as the working material. The structure consists of a system of links that can be additively manufactured as linked panels. The design of the links allows for the panels to be de-constructed and reassembled by hand to easily create the desired forms and shapes [67].

The links consists of 4 connected spiral arms connected on the top face but open on the reverse Figure 13, enabling the links to be disconnected and reconnected to other links creating garments with no size restrictions by connecting the printed panels of links. The links shapes are designed to obtain flexibility for elongation of the textile piece and to be firm enough so that the degree of stretch is achievable without breaking; also, a certain degree of strength is needed to withstand the manual process of reconstruction [67].

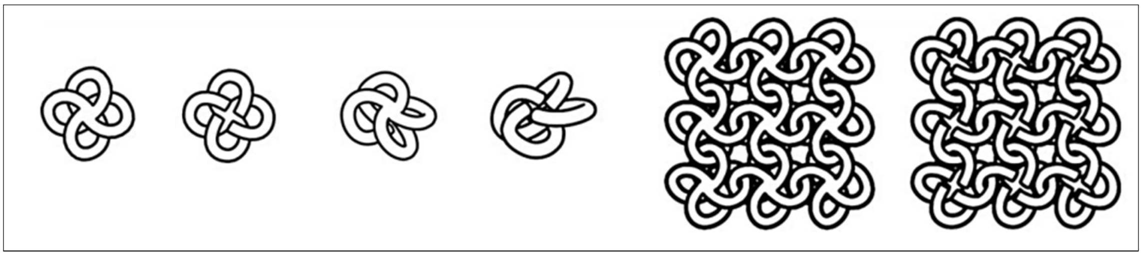

Figure 13: Modeclix printed links and panels [67].

The garments prototypes have been constructed from small panels of 22 x 22 links and assembled on a small workshop as traditional dress making. The garments are seamless and do not require the usual pattern making techniques, the material can be easily manipulated by everyone just by becoming familiar with the technique of connecting the links. Once the procedure is learned the connection of 50 links just takes approximately 1 minute [67]. The material can also be properly dyed making use of commercial textile dying processes.

Figure 14: Modeclix chocolate mint dress [68]

Sustainable manufacturing

The model of Modeclix offers significant advantages for the development of a more sustainable textile industry with the employment of Circular Economy principles.

The AM process allows for an on demand manufacture of material, the scalability of the process efficiently meets the economic requirements and extends the lifetime of the products with the option of re-configure and re-purpose the material at any time during the product lifecyle. The re-configuration process enables the creation of garments that perfectly fit the customers by simply removing or adding links which entails considerable material savings in the manufacturing process, it also creates a greater sense of comfortability between the customer and the product as it perfectly adapts to the body shape, the possibility of changing the clothes in length or shape would also be available when required.

The recovery activities as repair, remanufacture and recycle are easily performed in the Modeclix manufactured products. The interchangeable links enables a straight forward repair process, if a piece of the product is damaged at any time of the product's lifecyle only the required links are substituted for new ones keeping the rest unaltered. The recycling of the material is performed as a reuse process as the used material can be incorporated in the manufacturing of a new product. The modularity offered by Modeclix enables an ecosystem where all products can be re-used or re-purposed across a variety of products and services.

Resource efficiency is also a key advantage in the use of the Modeclix model. The manual assembly process allows for the creation of a wide range of products with the same material and without the need of post-processing activities. Product customization is also easily obtainable and does not require for any changes in the production process. There is an overall reduction of the number of processes needed to obtain the final product; this is translated in a reduction of energy and material use and a reduction in the greenhouse emissions generated in the process.

As one of the main advantages of Additive Manufacturing the model of Modeclix also offers the possibility of promoting localized production as the required infrastructure of the manufacturing process can be decentralized with the expansion of AM centers around the world. Furthermore, the assembly process it is suitable for promoting local workshops that will certainly reduce the transportation and the delivery times as well as promote the reuse and repair activities.

The Modeclix model is indeed promising and shows part of the sustainable potential benefits that the usage of AM in the textile industry could generate. However, the model despite being able to produce acceptable cloths is still far from market demand and will require a further development in the manufacturing technologies and more importantly a big change in the textile industry patterns.

Waste generation in construction and buildings

The construction sector is one of the pillars in the economic and sustainable development of a country; the performance of the sector is directly related with the quality of the citizens' life as it provides necessary socio-economic infrastructures such as roads, hospitals, schools and so on. The achievement of sustainability of the sector is not an easy task as construction activities require for a great amount of extracted resources, employing almost 50% of the extracted material and being responsible of almost 35% of the EU's total waste generation [65]. An *Ellen MacArthur* report about the circular economy challenges in cities [69], highlighted the main drivers for change to circular economy strategies for urban buildings shown in Figure 15, which suggests that the resource and energy consumption of buildings are the main sustainability issues of the sector and require for adequate transformations.

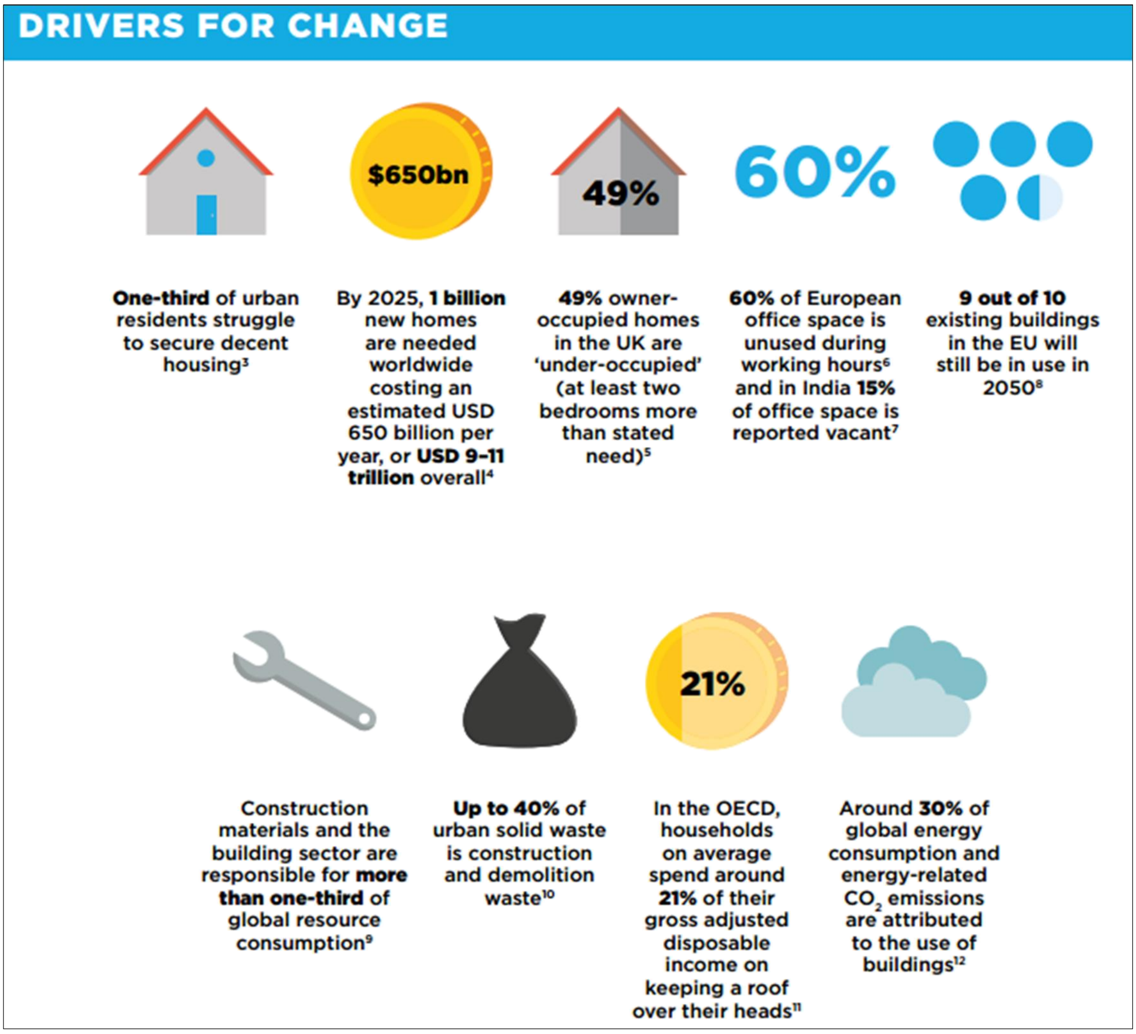

Figure 15: Drivers for change to circular economy in urban buildings [69].

An analysis of a building lifecycle reveals that the use phase of the buildings is the most demanding in terms of energy consumption, in the last years, great efforts have been made in order to reduce the environmental impacts derived from the energy intensity of the building use, the energy that requires a building in terms of calefaction, refrigeration and lightening has been substantially reduced with the introduction of improved building isolation, renewable energy sources and advancements in equipment efficiency. These measures are now becoming requirements for the construction of new buildings in most of the developed countries. However, the environmental impacts related with the extraction, manufacturing and dispose of the construction products is still responsible for a great part of the buildings' emissions along their lifecycle, representing an estimated 5-12% of the total national GHG emissions in European countries, and the progress been made in this area is still weak [65].

Construction activities consume almost 38% of the energy used every year in the world, up to 20% of this energy consumption comes from the manufacturing process of the raw materials used as construction products [70]. Each construction material differ considerably in the amount of energy it consumes for the manufacturing process, wood for example have almost no energy consumption on its manufacturing process, however cement based materials, apart from being the most used materials in the construction processes, require for high amount of energy in their production process.

Another considerable environmental issue in the construction sector is the generation and management of the waste that is produced mainly in the construction and demolition phases of the building. The waste generated during the construction phase is normally due to inefficient management operations like last hour design changes, poor planning or ordering errors among others [71]. The waste linked with the demolition or refurbishment phase can be generated for various reasons, the two main ones are:

- The inefficiency or absence of a proper recycling system for the disposed material, that ends up with the material being landfilled, with the environmental dangers that this entails.
- Bad demolition process, this occurs when the materials are mixed together and as consequence the sorting process is disabled and the recycling process prevented.

All these environmental challenges that present the actual model of construction should be addressed as fast as possible, for that reason innovative processes should lead the way into the transformation of the sector.

Concrete 3D Printing

Concrete or cement based products as mentioned before are by volume the most widely used building materials all over the world. Concrete is mainly comprised of three elements: Water, aggregate and Portland cement. Its manufacturing requires for a large amount of energy mainly derived of the production the Portland cement, that is accompanied with the emission of large quantities of greenhouse gases.

Despite the environmental issues related with concrete utilization there are many benefits that this product brings to the construction industry. Regarding the mechanical properties, concrete is characterized with good strength, a great durability, exceptional fire resistance and a flexibility that provides a considerable design freedom; it is also considered a low cost product and the raw materials for its production can be found anywhere [72].

Concrete 3D printing appears as a good tool to reduce the environmental impact of the conventional use of concrete in buildings. The main modification that supposes the implementation of this new technology is the suppression of the formwork, an essential step in the construction work of the conventional concrete structures. The absence of formwork as [72] points out will entail certain benefits:

- It could save 35% to 60% of the monetary expenses of concrete construction by reducing formwork expenses, less construction time and labor will be required.
- Incidents and fatalities will certainly be reduced, shifting the workforce to a more skilled and technology oriented one.
- The waste generated during construction will certainly be reduced as the manufacturing process will be accurately controlled and the material consumption will be optimized.

The majority of the developed concrete printers are based on the Contour Crafting technique that is based on Fused Deposition Modelling also known as Material Extrusion, the printing machine can be a robotic-based or gantry-based printer. The construction with Contour Crafting normally takes place on-site, with other printing methods exist the possibility of printing off-site and assemble on-site [72]. The printed concrete differs from the conventional concrete mix, it combines the features of self-compacting concrete, that does not need for vibration and sprayed concrete that provides the aim of freeform construction; there is not an standard composition for the concrete as the material mix varies from different providers [72].

One of the most demanding challenges that the concrete 3D printing process confronts is the achievement of a proper printing quality and capability. Poor printing quality can affect the mechanical properties of the concrete and reduce the service life of the printed structures. Layer effects are harmful to the quality of the printed elements, the layer dimension will determine the performance of the material, small layers will improve the printing resolution but also will require for more printing time, also the inter-layer strength is reduced when the time interval within layers is augmented, so a proper balance is needed. The printing capability is the ability of the printer to create curved structures that is dependent on the stiffness of the concrete when extruded [72].

How concrete 3D printing can reduce CO_2 emissions?

The reduction of the CO_2 emissions using concrete printing can come from different ways. The first is by using a concrete mix which manufacturing process requires for a lower amount of energy and in consequence generates less CO_2 emissions. In order to achieve it, the concrete mix should reduce the quantity of Portland cement of its composition by incrementing the quantity of aggregate, however this increment will lead to higher yield strength of the fresh concrete that can difficult the extrusion process, that is why the proper mix that reduces the quantity of cement and at the same time it can be properly extruded is still being researched [72].

Other way to reduce the total CO_2 emissions is by designing optimized structures and irregularly-shaped element directly; these elements are able to generate the same strength with less amount of material, however, as mentioned before, for the construction of complex structures a certain degree of stiffness is necessary in the extruded material that is not always achievable with the actual technology. Also, for large concrete structures that require steel reinforcement permanent precast formworks can be constructed that are filled with fresh concrete in-situ after placing the steel bars into the mold [72].

Despite the previous promising methods for reducing emissions, the primary reason for reducing CO_2 emissions is the absence of formwork. The energy input for making the molds is eliminated; lower amounts of material waste are generated reducing the amount of material needed and eliminating the energy needed for dealing with the waste. Also, the decrease in labor can entail a reduction in CO2 emissions as less machinery is needed and less emissions from workers moving to the construction site can be produced [72].

Case studies

A number of companies and research centers have developed their own printing system and some of them are starting to commercially sell their services around the world.

The Shanghai located company *Winsun* is one of the pioneers in the industry as it was able to invent back in 2005 the spray nozzle, one of the key components of 3D concrete printers. Also in 2013 the company surprised the world with the first successful print of a residential house, the construction of the house was performed with a prefabricate approach as the walls were printed in a factory and then assembled on site. With this technique the company claims to significantly increase the speed of construction, in fact they were able to print a three-storey 1,100 sqm mansion Figure 16 that just took one day of printing and two day of assembly requiring the work of only three workmen [73].

Figure 16: Wujiang 3D Printing Three-storey Villa [73].

Winsun is also able to obtain a great degree of environmental sustainability in their process, apart from the above mentioned advantages of the 3D concrete printing in the reduction of CO_2 emissions, the company claims to reach a 50% of recycling in their concrete mix by using materials from construction waste as aggregate [73].

Another 3D concrete printing company, *BE MORE 3D* located in Spain, is able to build residential homes of 70 sqm in less than 12 hours. The printing machine used is a gantry port that can be easily transported just taking the handwork of 3 operators and less than 4 hours to be assembled [74]. This allows the company to print the houses in situ anywhere without the need of a factory or similar. The report of the company technology description [74] summarizes the construction process of the mains structure of a printed residence Figure 17in 6 steps:

1. The model of the residence is designed using any 3D design program and then the model is sliced to obtain the necessary input for the printer.
2. The terrain where the model will be constructed is set up by degrubbin and land levelling. Then a reinforced concrete base is placed that will serve as foundation and zero level mark.
3. The machine is assembled in the previous spot and the required materials are stockpiled.
4. The concrete adequate mix is prepared and the material is supplied trough a concrete pump from the mixer to the printer.
5. The material is extruded layer by layer making sure the planned facade voids are left open and stopping when lintels and framework are required to be placed. For the doors, wooden frames will be placed and on top steel will be placed as support.
6. Finally the desired deck is placed with the building installations above and a compression concrete layer is applied.

Figure 17: Construction process BE MORE 3D [74]

BIM and Augmented reality for waste reduction

As previously mentioned the generation of waste in the construction activities is one of the great concerns for the achievement of sustainability in the sector. The waste generation is produced manly at the end of life in the demolition process; however, due to inefficient planning, poor quality of materials, low skilled workers or bad site management activities, a considerable amount of waste is generated during the construction process.

Digital technologies represent a great opportunity for the management of waste, providing tools for reducing the waste along the lifecycle of buildings. A well-known simulation tool in the construction sector that is becoming essential for all the construction sector stakeholders is the Building Information Modelling (BIM), it can be defined as the digital representation of the physical and functional characteristics of a facility that allows for design, construction and operation process that forms a reliable basis for decision-making during its lifecycle [75]. Augmented Realty applications shows as well a great potential for construction operations particularly combined with BIM systems as it will be shown in the following paragraphs.

BIM and AR application for improving construction performance

The construction industry is based on project works usually subjected to cost overruns and schedule deviations; in fact 70% of the projects are affected by time delays, with 14% of the project contract sum consumed by cost overruns and 10% of project materials ending up as waste [75]. The main cause of this misalignment is mainly due to problems and deficiencies in the management of construction processes, the authors in [75] identified the following as the main ones:

- Low labor productivity causing costs and time overruns.
- Low productivity caused by waste generation due to inefficient construction planning and site management, poor quality, ineffective control and lack of information.
- Lack of automation in controlling and monitoring construction works, as managers often use paper-based or simple IT tools that do not efficiently control the progress and performance.
- Lack of information, which often leads to communication issues and construction errors.

In order to address some of the previous problems the development of the *AR4C* tool started, a BIM-based application enhanced with AR technology and combined with a location based management system. Developers have already created similar applications and some of them are already available in the market, however *AR4C* is characterized for providing a one field tool that is able to support lean construction on site and the visualization of content to streamline information related to the project and the construction process, it allows for a monitoring of project evolution according to the lean methodology and a location based visualization of construction progress and performance [75].

Figure 18: AR4C application used in construction site [75].

The proposed solution of *AR4C* aims to improve performance of construction such as productivity, quality of work and information flow. Productivity will be enhanced by implementing monitoring of the construction on a daily basis in a specific location of the project. By overlaying a 3D BIM model on the real world using AR according to [75] the following tasks will be achieved:

- Project control via rapid identification of deviation from project schedule as well as variation in performance and progress.
- Increment in quality of construction work by providing context specific information on tasks, building components and materials anywhere and anytime.
- Verification of construction work by linking quality checklists to each construction task.
- Streamline the information flow by displaying tailored information for each construction task.

The *AR4C* application prototype is still in its development phase and it is already showing promising results, when used for the construction of a school according to the architects and site managers the construction progress and performance metrics reduced the time needed by 50% compared with conventional procedures, however it has also revealed some problems in the alignment of the 3D building in AR as the model was not always perfectly superimposed above the real objects [75], a feature that should be improved in order to deliver an efficient application.

BIM for buildings' End-of-Life scenarios

Building Information Modelling is an adequate tool for implementing circular economy practices into the building sector, as it has the capability to accumulate lifecycle information about a building facilitating the whole life management of a building from planning to operation.

When it comes to the proper assessment of the End-of-life phase of the buildings, BIM has shown a considerable potential mainly in the reduction and management of the waste generated during the demolition and dismantling process. BIM allows for the introduction of new layers of information to each object in order to prepare them for future EoL operations such as deconstruction guidelines, environmental assessments or legal requirements [76].

For deconstruction activities having a digital model of the building helps with monitoring the overall status and health of the components as well as getting access to the planned deconstruction guidelines. Moreover, deconstruction is an activity that can take place 50 years or more from the time the building is designed and constructed, normally new parties that didn't took place in the Beginning of Life phase of the building will require information about the quantities and qualities of materials as well as the need to perform necessary measures, BIM provides access to all this required information whenever needed [76].

In order to obtain the maximum value from the EoL of a building by recycling or reusing its materials the building components must be effectively retrieved after the lifecycle of the building is finished. Design for Deconstruction (DfD) has proven to be the best strategy to effectively maintain the value of the building materials at the end of the building's lifecycle; nevertheless DfD is not a guarantee for a successful deconstruction process as it is dependent on technical and non-technical success factors. Some studies appearing in [76] have proven how the implementation of BIM models for DfD strategies certainly enhance the deconstruction process, as BIM helps with the estimation of EoL properties of materials while improving the disassembly process.

Recycling and recovery in the Electronics and ICT sector

The massive increase in the usage of new technologies has led to an over production of electronic and electrical equipment, fast product upgrades and technological trends are incrementing product obsolescence, driving shorter product life usage and generation of waste. In fact, in the EU this source of waste has become one of the fastest growing ones with an annual increment of 2% and an estimated recycling rate of less than 40% [65].

This particular waste named as 'e-waste' or Waste Electrical and Electronic Equipment (WEEE), is of particular value as electronic devices have high demand for earth elements and precious metals. In particular 'smartphones' as shown in Figure 19 can be made of 30 different elements of the periodic table some of them being in serious threat for their availability like Yttrium (Y) or Arsenic (As), and others considered hazardous as they suppose a threat to the environment if the products are not adequately treated before ending up in a landfill.

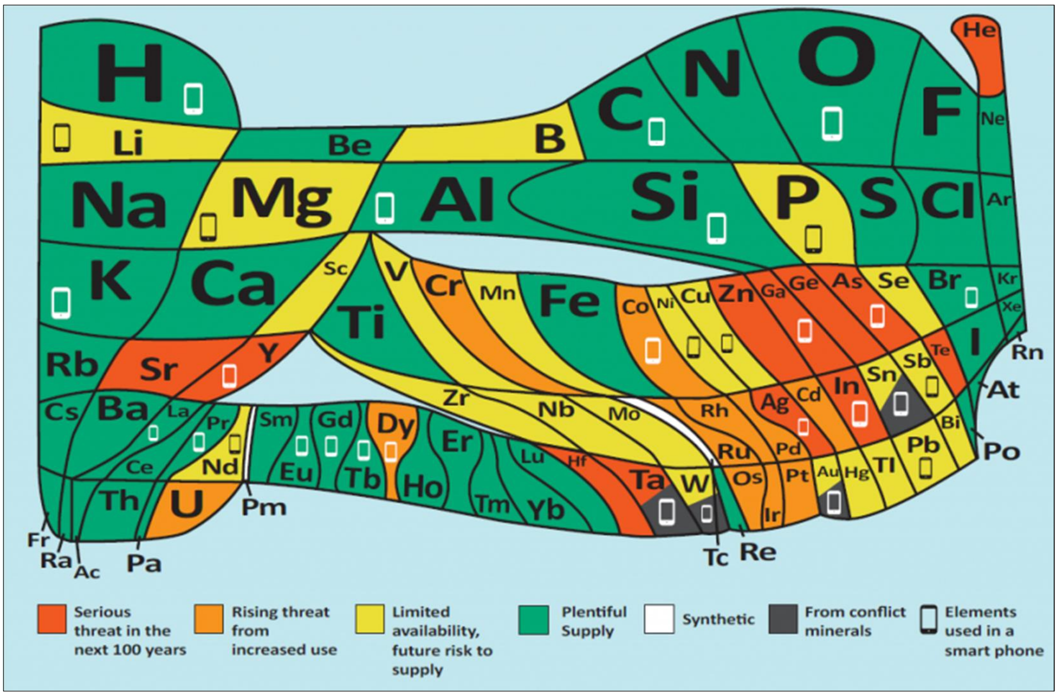

Figure 19: Phones' elements periodic table [77]

In the last years European countries, United States or Japan have implemented strict measures regarding the dispose of consumer electronics, however this has ended up with illegal transportation of waste from developed to non-developed countries, where the so called informal recycling is performed. The reasons for this movement of waste through the world is mainly due to economic reasons; less developed countries as India, China or Nigeria are becoming the perfect places for these practices as their status of labor, the economies of scale and the lack of regulations and taxes are ideal supporters of this situation [78]. Even though the process of recycling is still conducted in these countries, the fact that these countries have less environmental regulations and the recycling process are inefficiently performed, suppose a real threat to the sustainability of the process.

Another critical issue is the low collection rate of WEEE, which as identified by [78] is mainly related with the lack of information about the production, consumption and disposal of the electronic products. This ends up with a legislation based on statistical data that in most cases is quite far from reality, generating inefficient measures and also overlooking the environmental impacts that informal recycling could be generating.

The last design improvements that generate better marketability and durability of the products also create recycling challenges in the separation of the components and material recovery, for example lamination of components in Printed Circuit Boards (PCB) increase durability of components while reducing their size but hinder the disassembly and recovery of materials [79].

The authors in [80] according to experts' opinions identified the following barriers as the most common ones for implementing component recovery and material recycling of e-waste:

- *Quantity recovery processes*. The volume and diversity of WEEE, difficult the establishment of universal operations. Disassembly processes are hinder by product miniaturization and materials are hardly differentiated.
- *Lifetime.* Products' lifetime are unpredictable, used materials are easily broken during material recovery and their status is not easily recognizable. The fast evolution of the market is an obstacle in reallocation of recovered products.
- *Recovery cost.* In some cases the recovery process is more expensive than the purchasing of new products due to the special facilities and skilled operators required. Transportation is also a drawback as in many countries hazardous materials need specific permissions for being transported.
- *Awareness.* The current markets lack of awareness of social and environmental factors is a barrier for resource recovery activities. Consumers usually prefer brand new products than the ones made from recovered products. Disposal points are unfamiliar for many consumers and in many countries are just parts of the municipal waste.

- *WEEE chain.* The recovery network involves many participants and its complex to manage without proper information; particularly end users are the less involved ones.

Some of these above mentioned barriers could certainly be minimized with the implementation of eco-design strategies that will reduce the hazardous material compositions and will ease product disassembly and recovery processes, also adequate legislations and policies will make producers and consumers more aware of the existing problems and will mitigate risky activities.

In the next section some proposed solutions involving the adoption of new industry 4.0 technologies tacking the challenges in disassembly process and WEEE chain management will be analyzed.

Apple's Daisy robot

Autonomous Robots have not been included in the previous chapter of the key Industry 4.0 technologies as they are considered to be a quite well known and settled technology, nevertheless they are significantly important in the implementation of this new industry. Autonomous Robots are essential for achieving flexibility in the production system and when supported with smart ecosystems they can enhance the production processes to the next level. The following case study exemplifies how a robot can support a recovery process almost impossible for manual work.

With the ambition of achieving a usage of only recycled and renewable materials in the near future, *Apple* among other initiatives has designed a robot capable of separating components and recovering materials of a total of 15 different iPhone models.

Daisy, the new model of this robot is capable of disassemble 200 phones per hour and in the year 2017, a model of the robot located in Austin processed 1 million in total.

The principal aim of the robot is to remove and sort components in a way that materials can be recovered with a higher quality and quantity than traditional recyclers. As mentioned before the disassembly process is one of the main problems of material recovery in the electronic products, *Daisy* is able to successfully sort the components which then are sent to the recycling plants where the materials are easily separated and recycled [81].

The robot starts by separating the screen and the phone body by introducing a set of prongs between them, then the screws are removed and the battery that is glued to the phone's body is removed by blasting the glue with freezing air and then knocking it with enough force. After that the logic board is separated by punching out the screws that hold it, for doing so the robot has to first identify the phone model. Finally, *Daisy* removes the cameras, haptics, speakers and other bits. Figure 20 shows the final disassembled pieces after the process, indicating the material of each piece and the potential for material recovery of every 100,000 phones.

Figure 20: Components and materials disassembly robot Daisy recovers [81]

Digital Twin and Cloud Computing for WEEE chain management

The supply chain management of e-waste is as mentioned before, one of the main challenges in the deployment of an efficient recovery system. Researchers have been working in several solutions for these problems by implementing digital systems into the management structures, for instance in [78] the researchers proposed a system based on BigData applications where IoT devices are used to record and collect information along the product lifecycle allowing for a full monitoring of the waste and the recycling activities. A similar but more complex approach based on the capabilities of Digital Twins is provided by [82] and is introduced in the following chapters.

Tracking products' status along their value chain is of great importance as remanufacturers and recyclers need deep knowledge of the product to effectively perform the required operations. However, in practice the actual system does not enable the acquisition of this information. A big portion of the product lifecycle information is lost during the product development and manufacturing, also the information flow is almost stopped when the product arrives to the end user, examination of products performed by product collectors can recover some amount of lost information but still the system remains ineffective in communication terms [82].

System integration, data utilization and connectivity are identified as the main challenges in the development of a WEEE management system; Digital Twin according to [82] shows high potential in solving these challenges by merging the data from the physical world and the software into a cyber world. DT can be assumed as the key to achieve a cyber-physical system bridging the cloud systems and the data from physical objects (IoT) or from other historical or software sources (BigData).

The proposed scheme or system architecture provided by [82] for data integration of the DT model is structured as follows:

1. Product design. The digital twin is initiated based on the knowledge from the product design and development phase. Geometry, components, materials and hazardous substances are the data input for the model.
2. Product status. When the product is sold to the end users, they have to update the product status via mobile apps, smart tags, websites or similar tools. Changes in product location and ownership or performed upgrades and repair operations are loaded in the model.

3. Logistics and exam results. Once the product comes to the end of its life the consumer dispose the product in an adequate collection point that is indicated trough the mobile app or website. After the collection the product can be examined and updated in consequence, with all the available information of the model the recovery operations are planned.
4. Recovered materials or components. The recycler or remanufacturer initiates the operations without the need of additional test or evaluation as all the needed information is stored in the DT. All the information of the recovered or reconditioned components is recorded in the new product's model.

The architecture model of the proposed Cyber Physical Systems is shown in Figure 21 where the computing resources needed and the information exchange along the different product lifecycle phases is characterized.

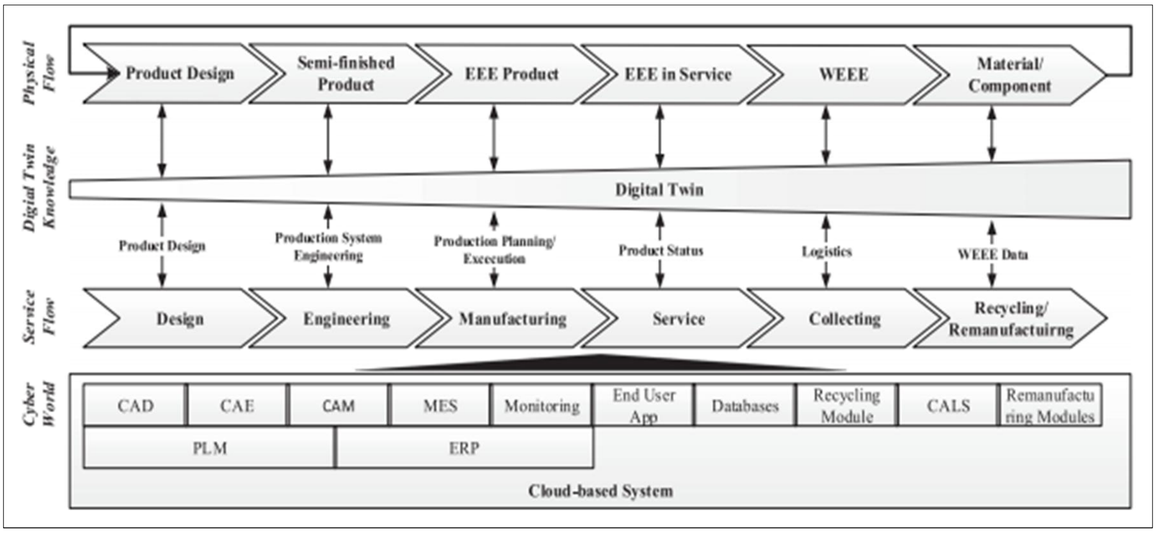

Figure 21: WEEE digital twin-enabled cyber-physical system [82].

The computing capabilities of the system are supported by a Cloud Computing environment that contains and provides the computing modules when needed. Through the product beginning of life all the operations and data gathering is coordinated by the Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP) systems. The product design begins with the CAD module where functional and environmental features of the products are documented. The Computer-aided Engineering (CAE) simulate the performance of the product to validate the product design. Environmental performance of the product can also be simulated in this stage making use of Life Cycle Assessment (LCA). During the manufacturing process operations are controlled by the Manufacturing Execution System

(MES) that through smart monitors and embedded sensors in IoT networks feeds the DT model with data collected from the factory. Through the product beginning of life all the operations and data gathering is coordinated by the PLM and ERP systems.

Once the user gets the product, as mentioned before, there are different possibilities of updating the information: RFID readers that are affordable devices for general usage, Near-Field Communication (NFC) available in the majority of smart phones or Quick Response (QR) tags that are able to record up to 1264 characters and are easily scanned with smart phones. It is worth to mention that before the user updates information about the product all the DT models are universal and is when the user makes the first changes that the product becomes distinguishable through its unique ID.

After the product ends its service the Computer-aided Logistics System (CALS) stablish the logistic strategy for collection, when the product reaches the remanufacturer/recycler specific computing modules for each operation make use of the DT data to perform the required operations.

The integration of DigitalTwin in the WEEE management has not reached the commercial use yet, however in [82] the feasibility of the system has been proven with model experiments. Nevertheless, there are certain limitations for the implementation of this system; intellectual property is one of them as producers may not want to share their product designs and technical information, also at a policy level the extended producer responsibility needs to be further improved, to encourage the engagement of all stakeholders.

Conclusions

Through this chapter the main conclusion that can be extracted from the paper are outlined. These conclusions can be divided in three groups, the ones related with the implementation of a Circular Economy, the ones concerning the topic of Industry 4.0 and the ones that indicates how Industry 4.0 can speed up the transition to a CE.

Circular Economy implications and feasibility

The development of a consolidated Circular Economy system holds the potential of solving many of the sustainable related issues that human society faces nowadays. Its main target of reducing the overall consumption of resources is proved to be a major opportunity to minimize the environmental impact of the actual consumption system, CE is also expected to generate new jobs around the value maintenance of materials through their lifecycle, achieving an auto sufficient structure where the dependency of certain countries from others is reduced and a greater state of equality can be attained.

In regards of the CE operation, it can be concluded that the principles in which it is sustained are not of great complexity at least from a theoretical point of view. Eco-design can be considered as the most relevant enabler of CE, a circular design enables the product to efficiently incorporate the value generating capabilities like its share ability, multifunctionality, reparability, reusability or recyclability among others. In addition product dematerialization, energy efficiency or material durability can be introduced in this phase. This places Eco-Design as the pillar from which Circular Economy practices should be constructed, as an efficient transformation has to start from the creation of new products that fits the system no by trying to fit the system into the actual products.

Even though the actual system is way too far from being circular there are clear indications that a circular system is achievable. Obviously technical innovations are required for the full implementation of a circular system; however these do not appear as the main obstacles for the implementation of CE. The main factor that slows down the process of transformation is the passive attitude and lack of commitment of people towards sustainability issues. Consumers do not demand sustainability and producers only take action when they are economically benefited. This is the main challenge that CE faces today and the way to address it is by first raising public awareness about the actual situation and then take action by introducing the adequate measures that start adapting people to the change.

By the moment policies in Europe as a reflect of society are starting to pave the way through a more circular system but are still far from achieving ambitious results. Policies are a must for transforming the system, however for policies to be effective and efficient they have to be aligned with the needs of the corresponding situation. Thus adequate measurement tools for Circularity are required, the existing ones are considered to serve as a preliminary approach to the problem but much more research and development is needed in order to create effective tools.

Industry 4.0 opportunities

The new revolution of the industry sector aims to bring information and connectivity to the next level, the accomplishment of these so called "smart" systems will create networks of connectivity where every piece of the supply chain receives, emits and process data. This great amount of data and information if properly treated can be converted in valuable knowledge for managing the system; the efficiency in all the processes of the supply chain from material extraction to after sales services can be enhanced and the coordination of the system will allow for a great degree of flexibility in the production process.

In order to successfully make the transition to Industry 4.0 there are some particular challenges that must be addressed. Companies and particularly SMEs face technical and economic challenges for implementing 4IR systems in their businesses such as investment requirements and lack of knowledge and expertise. Besides that, cybersecurity issues are one of the most discussed challenges, as the risks that arise with the full digitalization of industry can generate uncertainty between stakeholders. Also the energy consumption of the deployed technologies should be further studied in order to increment the energy efficiency of the designed systems.

Even though all the technologies of Industry 4.0 are key for constructing the ideal system Internet of Things and Additive Manufacturing are considered as the most significant ones. IoT is the one in charge of creating the smart ecosystem in which everything is connected; it works as the bridge from the physical to the digital world through sensing technology. Of course it needs from technologies like BigData for processing the information, Cloud Computing for managing the network and its potential can be maximized trough simulation technologies, but the core of this connectivity system is founded in IoT.

On the other hand AM is detached from the previous ones as its potential is not directly related with data and connectivity. Nevertheless AM brings a new paradigm into the manufacturing context as it completely transforms conventional processes, AM introduces many potential benefits like better customization, direct translation from design to manufacture or potential approach to zero defect manufacturing among others. Nevertheless is its ability to translate production to wherever required which holds the biggest potential to transform the manufacturing supply chain, as delocalized and centralized production systems can be transformed into extensive and localized systems that can generate new frameworks of opportunities, particularly for digital businesses.

Industry 4.0 for Circular Economy implementation

Industry 4.0 technologies bring about a series of capabilities that can report benefits in the implementation of a Circular Economy system. In fact the majority of improvements that these technologies introduce in the production processes can be associated with benefits for CE as both Circular Economy and Industry 4.0 despite doing it from different perspectives and with different visions are based on the same core principle that is to achieve optimized processes.

Some of these benefits are directly translated from an increase in the overall efficiency of the production processes. Traceability of materials enables resource optimization and waste reduction in the production processes, knowledge about assets enables predictive maintenance, optimization of inventories reduces material and energy needs, quality improvements extend the use phase and reduces waste and the match of supply and demand reduces waste, overproduction and transportation.

Besides that not all the benefits that Industry 4.0 brings to CE are a direct translation of the optimization of current processes. Digitalization brings up the possibility of creating new business models that can promote CE principles such as the share of assets, the dematerialization and multifuntionality of products and enables a greater capacity to provide services and aftersales operations that extend product lifecycle.

Also the ability to manage complex networks through information flows based on IoT systems is another great potential of Industry 4.0 for implementing Circular Economy. The cascade and loop approach of CE requires for the existence of an extensive supply chain with big number of operations and lot of valuable information sources. Once the products are tracked through their whole lifecycle the management of recovery operations is much more easily conducted as the case studies of *CircularID* protocols and the WEEE chain can illustrate. Furthermore, this knowledge about the product lifecycle serves as the perfect tool for measuring circularity, evaluate the progress and act in consequence improving products, businesses and policies and instructing people about CE.

Additive Manufacturing entails other benefits for the implementation of CE. The main ones are derived from the ability to design products that fit into circular strategies like: Use of low-impact or recycled materials, product shapes that encourage dematerialization or product design for reuse or remanufacture among others. Also the ability of AM to relocate manufacturing process near the consumption point reduces the needs for transportation and promotes localized recovery activities. The case studies of Concrete 3D printing and *Modeclix* represents the above mentioned abilities as the first enables dematerialization of the construction process and the latter supports product recovery activities.

Despite these findings the development of this topic is still considered to be weak as the majority of the existing studies are recent and do not address all the existing challenges. Also most of the analyzed case studies are still at experimental phase or are not jet commercially fully developed. As consequence more research and development activities are needed in order to extract the greatest potential of Industry 4.0 technologies in the implementation of a Circular Economy.

.

Works Cited

[1] EIT Climate-KIC, "Digitalisation –unlocking the potential of the circular economy," 2018.

[2] International Resource Panel (IRP), "Global Resources Outlook 2019: Natural Resources for the Future We Want," 2019.

[3] EEA, "The European environment state and outlook 2015 — Assessment of global megatrends," European Enviroment Agency, 2015 a.

[4] Commonwealth Scientific and Industrial Research Organization (CSIRO), "Welcome to the Anthropocene Planwt Boundaries," 2012. [Online]. Available: http://www.anthropocene.info/planetary-boundaries.php. [Accessed 31 August 2020].

[5] P. Schroeder, K. Anggraeni and U. Weber, "The Relevance of Circular Economy Practices to the Sustainable Development Goals," *Journal of Industrial Ecology,* 2018.

[6] M. de Wit, J. Hoogzaad and C. von Daniels, "The circularty gap report," CircleEconomy, 2020.

[7] D. C. Pearce and R. K. Turner, Economics of Natural Resources and the Environment, Hemel Hempstead:Harvester Wheatsheaf., 1990.

[8] V. Rizos, K. Tuokko and A. Behrnes, "The Circular Economy.A review of definitions, processes and impacts," Centre for European Policy Studies, Brussels, 2017.

[9] S. Sauvé, S. Bernard and P. Sloan, "Environmental sciences, sustainable development and circular economy:Alternative concepts for trans-disciplinary research.," *Environmental Development, Vol17,* pp. pp 48-56, 2016.

[10] Ellen MacArthur Foundation, "Towards the Circular Economy. Economic and Business Rationale for an acelerated transition," 2013.

[11] EMF and McKinsey Center for Business and Enviroment, "Growth within: A circular economy vision for a competitive Europe," Ellen Mac Arthur Foundation and McKinsey

Center for Business and Enviroment, Isle of Wight, 2015.

[12] J. Morgan and P. Mitchell, "Employment and the circular economy. Job creation in a more resource-efficient Britain," Green Alliance, London, 2015.

[13] Circle Economy, "Jobs & skills in The Circular Economy. State of play and future pathways," Circle Economy, 2020.

[14] Material Economics, "The Circular Economy a Powerful Force for Climate Mitigation," Material Economics, Stockholm, 2018.

[15] A. Reichel, M. De Schoenmakere and J. Gillabel, "Circular economy in Europe: Developing the knowledge base," European Enviroment Agency (EEA), 2016.

[16] J. Witteveen, "From assets to access: High potential transformation of the capital goods industry," ING Economics Department, 2016.

[17] TNS Political & Social, "The use of the collaborative economy,Flash Eurobarometer 467," 2018.

[18] OECD, "Why new business models matter for green growth," Organisation for Economic Co-operation and Development, Paris, 2013.

[19] G. Rebitzer, "Integrating life cycle costing and life cycle assessment for managing costs and environmental impacts in supply chains," *Cost management in supply chains,* pp. 128-146, 2002.

[20] EEA, "EEA Glossary," 2001. [Online]. Available: https://www.eea.europa.eu/help/glossary/eea-glossary/eco-design. [Accessed 4th May 2020].

[21] A. Mestre and T. Cooper, "Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy," *The Design Journal,* 2017.

[22] Eurostat, "Generation of waste by waste category, hazardousness and NACE," 24 02 2020. [Online]. Available: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasgen&lang=en.

[Accessed 05 05 2020].

[23] D. Romero and M. Rossi, "Towards Circular Lean Product-Service Systems," *Procedia CIRP,* vol. 64, pp. 13-18, 2017.

[24] EEA, "Circular by design. Products in the circular economy," European Environment Agency, Copenhagen, 2017.

[25] EEA, "Paving the way for a circular economy: insights on status and potentials," European Enviroment Agency, Copenhagen, 2019.

[26] European Economic and Social Committee, "Circular economy strategies and roadmaps in Europe," *EU publications,* 2019.

[27] e. J. Kirchherr, "Barriers to the Circular Economy: Evidence From the European Union (EU)," *Ecological Economics,* pp. 264-272, 2018.

[28] A. de Jesus and S. Mendonça, "Lost in Transition? Drivers and Barriers in the Eco-innovation Road to theCircular Economy," *Ecological Economics,* pp. 75-89, 2018.

[29] A. Pheifer, "BARRIERS & ENABLERS to Circular Business Models," ValueC, 2017.

[30] TNS Political & Social, "SMEs, resource efficiency and green markets,Flash Eurobarometer 456," 2018.

[31] M. Saidani, B. Yannou, Y. Leroy and F. Cluzel, "How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework," *Recycling,* Vols. 2(1), 6, 2017.

[32] European Comission, "Measuring progress towards circular economy in the European Union – Key indicators for a monitoring framework," Strasbourg, 2018.

[33] V. Alcacer and V. Cruz-Machado, "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems," *Engineering Science and Technology, an International Journal,* vol. 22, pp. 899-919, 2019.

[34] A. Pereira and F. Romero, "A review of the meanings and the implications of the

Industry 4.0 concept," *Procedia Manufacturing,* vol. 13, pp. 1206-1214, 2017.

[35] McKinsey Global Institute, " The Internet of Things: Mapping the value beyond the hype," 2015.

[36] H. B. e. al., "The industrial internet of things (IIoT): An analysis framework," *Computers in Industry,* vol. 101, pp. 1-12, 2018.

[37] P. Charith , Z. Arkady , C. Peter and G. Dimitrios, "Context Aware Computing forThe Internet of Things: A Survey," *IEEE Communications Surveys & Tutorials,* 2013.

[38] S. Li, L. Xu and S. Zhao, "The internet of things: A survey," *Inf Syst Front,* vol. 17, pp. 243-259, 2015.

[39] C. Greer, M. Burns, D. Wollman and E. Griffor, "Cyber-Physical Systems and Internet of Things," *Special Publication (NIST SP) - 1900-202,* 2019.

[40] S. Oks, . A. Fritzsche and K. Möslein, "An Application Map for Industrial Cyber-Physical Systems.," in *Industrial Internet of Things.*, Springer Series in Wireless Technology.Springer, Cham, 2017, pp. 21-46.

[41] L. M. Vaquero, L. Rodero-Merino, J. Caceres and M. Lindner, "A Break in the Clouds: Towards a Cloud Definition," *Computer Communication Review,* 2009.

[42] P. Mell and T. Grance, "The NIST Definition of Cloud Computing," National Institute of Standards and Technology (NIST), Gaithersburg, 2011.

[43] X.Xu, "From cloud computing to cloud manufacturing," *Robotics and Computer-Integrated Manufacturing,* vol. 28, pp. 75-86, 2012.

[44] P. Escamilla-Ambrosio, A. Rodríguez-Mota, E. Aguirre-Anaya, R. Acosta-Bermejo and M. Salinas-Rosales, "Distributing Computing in the Internet of Things: Cloud, Fog and Edge Computing Overview," *NEO 2016, Studies in Computational Intelligence 731,* pp. 87-115, 2018.

[45] WINSYSTEMS Inc. Company, "Cloud, Fog And Edge Computing – What's The Difference?," 4 December 2017. [Online]. Available:

https://www.winsystems.com/cloud-fog-and-edge-computing-whats-the-difference/. [Accessed 26 May 2020].

[46] A. Gandomi and M. Haider, "Beyond the hype: Big data concepts, methods, and analytics," *International Journal of Information Mangement,* vol. 35, pp. 137-144, 2015.

[47] F. Tao, Q. Qi, A. Liu and A. Kusiak, "Data-driven smart manufacturing," *Journal of Manufacturing Systems,* vol. 48, pp. 157-169, 2018.

[48] Q. QI and F. Tao, "Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison," *IEEE Acess,* 2018.

[49] D. Mourtzis, M. Doukas and D. Bernidaki, "Simulation in Manufacturing: Review and Challenges," *Procedia CIRP ,* vol. 25, p. 213–229, 2014.

[50] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *Int J Adv Manuf Technol,* vol. 94, p. 3563–3576, 2018.

[51] A. Nee, S. Ong , G. Chryssolouris and D. Mourtzis , "Augmented reality applications in design and manufacturing," *CIRP Annals,* vol. 61, pp. 657-679, 2012.

[52] K. Wong and A. Hernandez, "A Review of Additive Manufacturing," *International Scholarly Research Notices,* 2012.

[53] C. e. a. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities," *Materials Today,* vol. 21, pp. 22-37, 2018.

[54] E. Petrie, "3D Printing / Additive Manufacturing Using Polymers - Complete Guide," Omenexus, 2018. [Online]. Available: https://omnexus.specialchem.com/selection-guide/3d-printing-and-additive-manufacturing-polymers-and-processes#content. [Accessed 23 June 2020].

[55] R. Jiang, R. Kleer and F. Piller, "Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030," *Technological Forecasting & Social Change,* vol. 117, pp. 84-97, 2017.

[56] L. Sommer, "Industrial Revolution - Industry 4.0: Are German Manufacturing SMEs the First Victims of this Revolution?," *Journal of Industrial Engineering and Management,* 2015.

[57] R. Waslo, T. Lewis, T. Hajj and R. Carton, "Industry 4.0 and cybersecurity Managing risk in an age of connected production," Deloitte, 2017.

[58] K. Wang, Y. Wang, Y. Sun, S. Guo and J. Wu, "Green Industrial Internet of Things Architecture: An Energy-Efficient Perspective," *IEEE Communications Magazine,* vol. 54, pp. 48-54, 2016.

[59] P. Lacy, J. Long and W. Spindler, The Circular Economy Handbook, Accenture, 2020.

[60] A. Hedberg and S. Šipka, "The Circular Economy: Going Digital," European Policiy Center, 2020.

[61] Ellen MacArthur Foundation, "Intelligent assets: Unlocking the Circular Economy potential," 2016.

[62] McKinsey Digital, "Industry 4.0 How to navigate digitization of the manufaacturing sector," 2015.

[63] E. Blunk and H. Werthmann, "Industry 4.0 – An opportunity to realize sustainable manufacturing and its potential for Circular Economy," *DIEM,* vol. 3, 2017.

[64] P. Rosa, C. Sassanelli, A. Urbinati, D. Chiaroni and S. Terzi, "Assessing relations between Circular Economy and Industry 4.0: a systematic literature review," *International Journal of Production Research,* pp. 1662-1687, 2019.

[65] European Commission, "A new Circular Economy Action Plan. For a cleaner and more competitive Europe," Brussels, 2020.

[66] EON, "The Connected Products Economy – Powering Fashion and Retail's Circular Future," 2020.

[67] M. Bloomfield and S. Borstrock, "Modeclix. The additively manufactured adaptable textile," *Materials Today Communications,* vol. 16, pp. 212-216, 2018.

[68] Modeclix, "#madewithmodeclix," 2020. [Online]. Available: https://www.modeclix.com/?page_id=503. [Accessed 14 August 2020].

[69] Ellen MacArthur Foundation, "Circular Ecconomy in cities," 2019.

[70] I. Yuksek, "The evaluation of building materials in terms of Energy Efficiency," *Periodica Polytechnica Civil Engineering,* pp. 45-58, 2014.

[71] J. Hussin, I. Raham and A. Memon, "The Way Forward in Sustainable Construction: Issues and Challenges," *International Journal of Advances in Applied Sciences (IJAAS),* vol. 2, pp. 31-42, 2013.

[72] Y. Chen, F. Veer and O. Çopuroğlu, "A critical review of 3D concrete printing as a low CO2 concrete approach," *Heron,* 2017.

[73] World Economic Forum, "Shaping the future of Construction," 2016.

[74] BE MORE 3D, "BE MORE 3D Technological description".

[75] J. Ratajczak, M. Riedl and D. Matt, "BIM-based and AR Application Combined with Location-Based Management System for the Improvement of the Construction Performance," 2019.

[76] A. Akbarieh, L. Jayasinghe, D. Waldmann and F. Teferle, "BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review," *Sustainability,* vol. 12, 2020.

[77] European Chemical Society, "Element Scarcity – EuChemS Periodic Table," 2019. [Online]. Available: https://www.euchems.eu/euchems-periodic-table/. [Accessed 14 July 2020].

[78] F. Gu, B. Ma, J. Guo, A. Summers and P. Hall, "Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study," *Waste Management,* vol. 68, pp. 434-448, 2017.

[79] B. Tansel, "From electronic consumer products to e-wastes: Global outlook, waste quantities, recycling challenges," *Environment International,* vol. 98, pp. 35-45, 2017.

[80] X. Wang, B. Lopez, W. Ijomah, L. Wang and J. Li, "A Smart Cloud-Based System for the WEEE Recovery/Recycling," *Journal of Manufacturing Science and Engineering,* 2015.

[81] Apple Inc, "Environmental Responsibility Report," 2019.

[82] X. Wang and L. Wang, "Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0," *International Journal of Production Research,* vol. 57, pp. 3892-3902, 2019.

Appendix 1

In this appendix the lifecycle design strategies proposed in [21] are showed

Life cycle design Strategies	Slow the loop	Close the loop
1 – Selection of low impact materials	a. Cleaner materials b. Renewable materials c. Lower energy materials d. Recyclable materials	a. Recycled materials b. Recyclable materials c. Biodegradable materials d. Lower energy materials e. Photodegradable materials f. Renewable materials g. Cleaner materials
2 – Reduction of material use	a. Reduction in weight b. Reduction in volume (transport)	a. Reduction in weight b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Less production waste e. Fewer/cleaner production consumables	a. Alternative (optimised) production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Minimal production waste e. Fewer/cleaner production consumables f. Renewable material & energy resources g. Industrial symbiosis
4 – Optimisation of distribution system	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode c. Energy-efficient logistics	a. Less/reusable/ biodegradable (zero waste) packaging b. Energy-efficient transport mode c. Clean & efficient energy logistics d. Elimination of logistics– "do it yourself" (e.g. 3D print at home with starch-based polymers)
5 – Reduction of impact during use	a. Lower energy consumption b. Cleaner energy source c. Cleaner consumables d. Fewer consumables needed e. No waste of energy/ consumables	a. Lower energy consumption b. Clean energy source c. Clean consumables d. Fewer consumables needed e. No waste of energy/ consumables f. Function as service (not product) g. Upgradability (modularity)
6 – Optimisation of initial lifetime	a. Reliability & durability b. Easier maintenance & repair c. Upgradability & adaptability d. Standardization & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation (e.g. emotionally durable design)	a. Reliability & durability b. Easy maintenance & repair c. Upgradability & adaptability d. Standardisation & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation i. Service for function maintenance (i.e. company takes back end-of-life product, replaces with new)
7 – Optimisation of end of life system	a. Reuse of product b. Remanufacturing/ refurbishing c. Recycling of materials d. Safer incineration	a. Biodegradability b. Remanufacturing/ refurbishing c. Recycling of materials d. Recollection of product for dismantling/material extraction e. Compostability f. Nutritional value (waste=food) g. Photodegradation h. Reuse of product i. Repurpose of product function j. Recollection system for product
@ – Development of new concepts / Product design review / Other design concepts	a. Dematerialisation b. Shared use of the product (ownership) c. Integration of function d. Functional optimisation of product (components)	a. Dematerialisation b. Shared use of product (ownership) c. Integration of function d. Functional optimisation of product (components) e. Function as service (not product) f. Circular business model

Life cycle design strategies	Bio inspired loop	Bio based loop
1 – Selection of low impact materials	a. Bio materials b. Recyclable materials c. Clean materials d. Biodegradable materials e. Photodegradable materials	a. Renewable materials b. Biodegradable materials c. Compostable materials d. Clean materials e. Bio materials f. Photodegradable materials
2 – Reduction of material use	a. Biomimicry & bionics (biological structures) b. Reduction in weight c. Reduction in volume	a. Reduction in weight (less material = less pressure on biological life) b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Lower/cleaner energy consumption c. Less production waste d. Fewer/cleaner production consumables e. Industrial symbiosis	a. Alternative production techniques b. Lower/cleaner energy consumption c. Cultivation d. Fewer/cleaner production consumables
4 – Optimisation of Distribution System	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode	a. Bio material packaging b. Energy-efficient transport mode c. Efficient distribution logistics – "grow it yourself" (e.g. mycelium - grow organism at home) d. Elimination of logistics – "do it yourself" (e.g. 3D print in house with starch-based polymers; cultivate material over structure in house; moulding bio waste materials etc.)
5 – Reduction of impact during use	a. Lower energy consumption b. Clean energy source c. Cleaner consumables	a. Clean energy source b. Clean consumables c. Fewer consumables needed d. No waste of energy/consumables
6 – Optimisation of initial lifetime	a. Biomimicry & bionics b. Dis- and reassembly c. Modular product structure (cell-like) d. Self-repair (e.g. self-sealing containers)	a. Reliability & durability (e.g. resistance to biodegradation before desired time) b. Easy maintenance & repair – e.g. self-repair & sustained growth (living materials)
7 – Optimisation of end-of-life system	a. Biodegradability b. Reuse of product c. Repurpose of product function	a. Biodegradability b. Compostable c. Solubility d. Nutritional value (waste=food) e. Compostability f. Photodegradation
@ – Development of new concepts / Product design review / Other design concepts	a. Biodegradability	a. Alternative (biological) production b. Shared cultivation of the material

Appendix 2

This appendix gathers the information about the circular economy drivers proposed in [61]:

- Extending the use cycle. Extending the lifetime of products, components and materials enables the reduction of raw materials in production processes and reduces the overall need for new assets. As previously mentioned most of the potential for extending the life of assets comes from the design phases where activities that cycle back materials and components and repair or maintenance activities are planned.
- Increasing the utilization. The utilization of an asset can be maximized either by sharing the access or by increasing resource productivity in operations. Into this value driver it is also includes designing out negative externalities and the use of renewable resources.
- Looping trough additional use cycles. Assets coming to their end-of-life can be cycled back with reuse strategies where the asset is use by a new user, remanufacturing process that enables the user to reenter the cycle or recycling where the materials of the used asset replace virgin ones.
- Regeneration of natural capital. Natural ecosystems should maintain and enhance their long term productivity by undertake the necessary actions. This preservation serves as foundation to maintain the value of natural resources and support sustainability.