POLITECNICO DI TORINO

MASTER'S THESIS IN ENGINEERING & MANAGEMENT

PROMOTING CIRCULAR ECONOMY IN THE EARLY DESIGN STAGES OF PRODUCT DEVELOPMENT WITH A FOCUS ON ADDITIVE MANUFACTURING PROCESSES

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ABSTRACT

PROMOTING CIRCULAR ECONOMY IN THE EARLY DESIGN STAGES OF PRODUCT DEVELOPMENT WITH A FOCUS ON ADDITIVE MANUFACTURING PROCESSES

Within the framework of Product Life Management, Circular Economy (CE) is an important concept that seeks to design out waste and pollution, keep products and materials in use and regenerate natural systems. As companies increasingly recognize the benefits of transitioning to a CE, there is a growing need for tools and methodologies to support the design of circular products and services.

This master thesis presents a Circular Economy Card Deck as a novel approach to facilitate the early stages of product development. The deck consists of 10 cards based on Morseletto's "Targets for a circular economy" work (Piero Morseletto, 2020), which represents mainstream CE principles and strategies and can be used by designers, engineers, and other stakeholders to generate ideas, evaluate options, and make informed decisions. Moreover, this thesis aims at deeper analyze the strong relationship between CE and Additive Manufacturing (AM), a rapidly growing and highly promising manufacturing technology that has attracted significant attention in recent years.

The results of a pilot study with design and engineering students (Master level) suggest that the Card Deck can support the exploration of CE concepts and facilitate the identification of circular solutions. The thesis concludes with a discussion of the potential benefits and limitations of the card deck approach, and its integration into a Product Life Management framework, and gives suggestions for future research.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

1

INTRODUCTION

Sustainable development and responsibility have emerged as a global trend in recent years, affecting individuals, states, and companies worldwide. It has become increasingly clear that companies with a strong commitment to corporate responsibility are gaining recognition from investors and customers alike, with the latter remaining more loyal even during times of recession. This introductory Chapter aims to provide a comprehensive understanding of sustainable development with a particular focus on how Agenda 2030 and its SDGs can promote Circular Economy (CE) practices and then, explain the aim and research questions, the research context, and the outline of the thesis.

The concept of sustainability was first introduced during the 1987 United Nations Conference on the Environment and was later elaborated upon by the World Commission on Environment and Development. Their report emphasized the importance of sustainable development, defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (UN, 1987).

In 2015, the United Nations adopted Agenda 2030 and its 17 Sustainable Development Goals (SDGs), which represent a significant step forward in promoting sustainable development.

Following are the 17 Goals listed:

- Goal 1: no poverty
- Goal 2: zero hunger
- Goal 3: good health and well-being
- Goal 4: quality education
- Goal 5: gender equality
- Goal 6: clean water and sanitation.
- Goal 7: affordable and clean energy
- Goal 8: decent work and economic growth
- Goal 9: industry, innovation, and infrastructure
- Goal 10: reduced inequalities
- Goal 11: sustainable cities and communities
- Goal 12: responsible consumption and production
- Goal 13: climate action
- Goal 14: life below water
- Goal 15: life on land
- Goal 16: peace, justice, and strong institutions
- Goal 17: partnerships for the goals

The SDGs are universal in scope and apply to all people around the world, representing an action plan for the benefit of the planet, people, and well-being. They aim to strengthen global peace and eradicate poverty in all its forms, with companies recognized as having a major role to play in achieving these goals by the 2030 deadline. As a result, companies are increasingly integrating the SDGs into their corporate strategies and communicating transparently with stakeholders about their corporate responsibility. Corporate social responsibility has been shown to increase stakeholder trust in companies, leading to a more positive impression of the company overall.

The 2030 Agenda prioritizes dignity and equality and requires the engagement of all sectors of society and the State for its implementation. Governments, civil society, academic institutions, and the private sector are invited to take ownership of this ambitious agenda and embrace it as a tool for creating fair and inclusive societies that serve the citizens of today and future generations.

The 17 SDGs, associated with the Agenda, provide a starting point for the countries to work towards the vision of sustainable development and analyze the means of its implementation. The SDGs also serve as a planning and follow-up tool for countries at the national and local levels, supporting their long-term approach towards sustained, inclusive, and environmentally friendly development through the formulation of public policies, budgets, and monitoring and evaluation instruments.

In recent years, sustainability has emerged as a key concern within the manufacturing industry as well. While this sector has long been recognized as a major contributor to economic growth and human development, it is now widely acknowledged that manufacturing also carries significant environmental risks and externalities.
The overuse of resources by manufacturing industries has been particularly concerning, given the finite nature of many natural resources and the potential for long-term damage to ecosystems.

Overall, sustainability has become a critical issue for the manufacturing industry, with the need for more responsible and environmentally conscious practices becoming increasingly urgent. By embracing more sustainable approaches to manufacturing, businesses can not only reduce their environmental impact but also improve their long-term viability and competitiveness. This has led to growing calls for more sustainable practices and technologies within the manufacturing sector, including the development of CE that minimizes waste and resource consumption.

Additive Manufacturing (AM), also known as 3D printing, is an innovative technology that can help companies in this, achieving sustainable production, reducing material waste by up and leading to significant cost savings. Additionally, the ability to produce products closer to the point of consumption can reduce transportation costs and emissions. Furthermore, AM can drive greater innovation and product customization, resulting in better products and customer experiences. While there are some challenges to overcome, the potential benefits of AM make it an attractive option for companies looking to improve their production processes and become more sustainable.

Aim and research questions

This thesis work stems from an understanding of the need for corporates to apply a more sustainable approach and move towards a CE, as outlined in the preceding paragraphs. This research aims to bridge the current knowledge gap between CE-related design theory and practice. The overall aim of the thesis is to investigate how the CE concept is currently interpreted and explore what knowledge, tools, and strategies might further support design for a CE in practice. In addition, the thesis investigates the role of AM as an important production system for empowering CE. By examining how the concept of CE is currently implemented, and to what extent this is done holistically and according to the underlying goals of the CE, the work seeks answers to whether discrepancies exist between CE-related design theory and practice and how such discrepancies might be addressed.

To address these aims, the following three research questions were formulated:

1. How is the concept of a CE currently interpreted and how can designers improve the awareness of CE concepts during the design phase of product development?
2. What knowledge, tools, and strategies could further support design for a CE in practice?
3. Which is the current situation regarding the relationship between AM, EDS, and CE and is there any possibility to expand this topic?

Research context

The thesis work has been conducted at the Product Design and Innovation Laboratory, (Laboratoire Conception de Produits et Innovation LCPI), a research laboratory of Arts et Métiers ParisTech, whose work is in the field of Industrial Engineering. The three missions of the LCPI (Teaching, Research, and Industrial Valorization) are closely integrated and feed a unique and federating theme: the optimization of the Design and Innovation Process. Their research activities benefit from both academic roots and a strong industrial partnership, which is an important vector of modernity and competitiveness for LCPI.

The LCPI team is multidisciplinary, as is the design process: its composition is mainly based on Engineering Sciences and Human and Social Sciences. It has a first-rate technological platform and is developing five centers of expertise: Virtual Reality Prototyping and Rapid Manufacturing, Innovation / Foresight / Creativity, Usage Analysis, Kansei Engineering, and Eco-design and Product Life Cycle.

This research thesis is a collaboration between Laboratoire Conception de Produits et Innovation at Arts et Métiers ParisTech and Politecnico di Torino.

Outline of the thesis

This thesis is structured as follows. Chapter 2 presents an overview of the CE framework, analyzing its definition, and the differences with the concept of *sustainability*. Moreover, a guide on how to pursue CE is given, introducing the Lean Manufacturing and Life Cycle Assessment concept as well. Chapter 3 describes previous research that is relevant to this thesis. Chapter 4 describes the overall research design and the methods used for the research. Chapter 5 discusses the findings in relation to the research questions and previous research and reflects on the research design and methods. Chapter 6 provides the conclusion and presents some directions for future research. In addition to these chapters, the paper resulting from this research study is appending.

2

CIRCULAR ECONOMY

The Circular Economy (CE) concept has its roots in the ideas presented by Kenneth E. Boulding in his work, "The Economics for the Coming Spaceship Earth". Boulding, in 1966, was the first to propose the idea of a cyclical ecological system capable of continuously reproducing materials. He acknowledged that the Earth's resources are finite and that pollution cannot be fully absorbed by nature. He argued that action must be taken to prevent the scarcity of raw materials and reduce environmental pollution, which could cause significant problems for society in the future and has gained significant traction in recent years as a potential solution to many of the environmental and economic challenges facing the world today.

From climate change and resource depletion to social inequality and economic stagnation, the CE offers a holistic and integrated approach to addressing these types of complex issues (De Abreu et al., 2022). By redesigning systems and processes to be regenerative and restorative, the CE aims to create value and prosperity while reducing the negative impacts on people and the planet (Velenturf and Purnell, 2021). As such, a literature review of the CE is timely and relevant, as it can help to identify the key drivers and barriers to the adoption of this model, as well as the opportunities and challenges it presents for enterprises and other stakeholders.

In recent years, there has been a significant increase in the number of published papers on the topic of CE. A search of the Scopus database identified 18,402 documents on this topic, with an increasing number of publications in the last 5 years, as shown in the graph in Figure 1. Data, presented in Figure 1, clearly illustrate the growing interest in the topic of CE in recent years, starting from 2016. In fact, in the top part, it is possible to detect that the number of published papers on this subject has consistently increased over the past decade, reaching a peak in the most recent years. This trend suggests that the concept of CE has gained significant attention within the academic community and is seen as an important area of study. In the bottom part of Figure 1, one can observe the number of documents published in each country. As represented in the graph at the right, the majority of these papers are classified as articles, rather than reviews. This suggests that researchers are actively contributing new findings and insights to the field, rather than simply summarizing and synthesizing existing knowledge (Gutierrez-Bucheli et al., 2022). Overall, the increasing number of papers on CE highlights the relevance and importance of this concept in today's world.

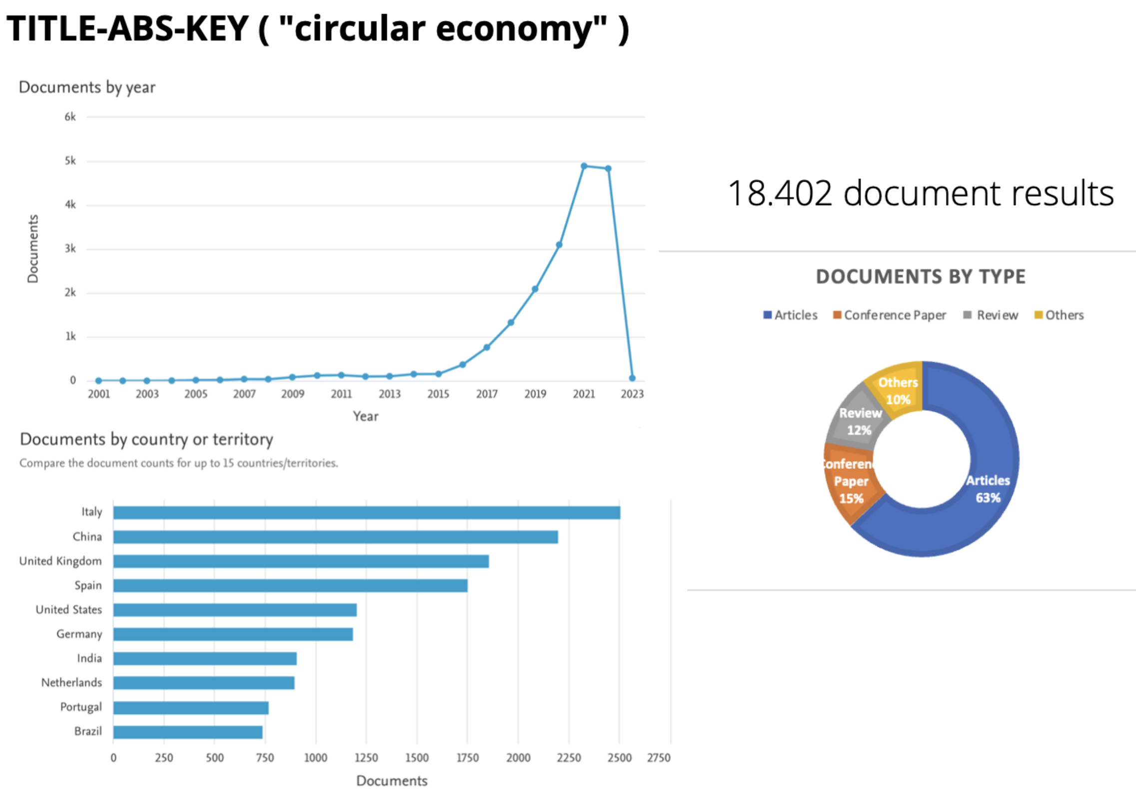


Figure 1 Results of "Circular Economy" research on Scopus.

The first step of this research consists of the collection of different definitions of CE. To reach this scope, more than 80 definitions of the term have been read and benchmarked considering the number of references and accuracy as well. Of these 80 definitions, the most interesting have been selected to deepen and understand the broad concept of the circular economy in more detail.

Circular Economy Definition

The CE is a broad concept, and more than one hundred definitions, offering multiple, sometimes contradictory, ways of conceptualizing the CE have been identified (Kirchherr et al., 2017). The CE concept has gained instigation both among scholars and interpreters.
Academic research on the CE has obtained significant attention in recent years, with several reviews on the subject having been published, including those by Andersen (2007), Ghisellini et al. (2016), Lieder and Rashid (2016), and Su et al. (2013). The Ellen MacArthur Foundation has played a crucial role in promoting the CE as well and has published a wealth of information on the subject, including a book by Webster (2015) and several reports (EMF, 2014, 2013a, 2013b). Moreover, several consultancies have seized the opportunities presented by the CE such as Lacey and Rutqvist (2015) and McKinsey (2013). Still, critics claim that it has numerous different meanings to different people and this can be justified by the fact that the field of CE has not 'matured' yet being such a modern concept, all the

possible paradigms of the framework still have to be explored (Geissdoerfer et al., 2017).

A CE is described as an approach that would transform the function of resources in the economy. From this point of view, waste from factories would become a valuable input to another process – and products could be repaired, reused, or upgraded instead of thrown away (Roberts et al., 2021). The French Environment and Energy Management Agency (Agence de l'environnement et de la maîtrise de l'énergie ADEME) in 2014 focused its definition mostly on the objective of the CE which is to reduce the environmental impact of resource consumption and improve social well-being. The Circular Economy Fund supports the implementation of the waste and circular economy policy in France to support local authorities and guide the behavior of stakeholders through investment in sorting, recycling, and recovery facilities as well as prevention actions.

The European Commission stresses the view of CE as an economy "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized''(Michelini et al., 2017). In particular, the European Commission aims to increase circular practices in the industrial sector, by examining ways to further encourage circularity in industrial processes, promoting industrial symbiosis through a reporting and certification system, supporting the sustainable and circular bio-based sector, encouraging the use of digital technologies for resource tracking, and promoting the adoption of green technologies through certification.
To simplify the CE concept, it could be reasonable to use as a starting point the three principles defined by Ellen MacArthur Foundation in 2013:

1. Rethink and redesign products and services.
2. Keep products and materials in use.
3. Regenerate natural systems.

During the last ten years, there has been a focus in the literature on the importance of using the principles of CE in a holistic, integrated manner, rather than as a standalone solution (Velenturf and Purnell, 2021). This suggests that CE is likely to be applied in practical ways, potentially in industrial settings, where it can be implemented as part of a larger system rather than being used in isolation.

Sauvé et al., in 2016, put forward a definition of CE that differs from the traditional linear economy approach. They argued that, while sustainable development in the linear model primarily concentrates on minimizing waste, recycling, and pollution, the CE model places a greater emphasis on resources and considers all inputs and outputs of the production process, with a specific focus on waste management. CE is an alternative to the traditional linear economy, in which we extract resources, use them to create products, and then dispose of them when they are no longer needed. Instead, in a CE, we aim to keep resources in use for as long as possible, extracting the maximum value from them, while they are in use, and then recovering and reusing products and materials once they are no longer needed. This helps to minimize waste, reduce resource depletion, and contribute to a more sustainable future. Synthesizing, a CE is an alternative to a traditional linear economy ("make, use, dispose of") in which we keep resources in use for as long as possible, extracting the maximum value from them whilst in use, then recovering and reusing products and materials (Ellen MacArthur Foundation and McKinsey & Company).

Lieder and Rashid's point of view declares that "the core idea of the CE is to transition away from the 'take-make-use-dispose' economy towards practices that keep the value of materials for much longer circular approaches such as "zero waste manufacturing" are being promoted to "eliminate waste across entire value chains to the fullest extent possible" (Lieder and Rashid, 2016). The definition of CE in contrast with a linear economy model will be analyzed in paragraph 2.1.4 and will represent the definition of the CE term that is decided to be considered in this thesis work.

Circular Economy and Sustainability

After listing some of the different definitions of CE presented in the literature, it is important to introduce the concept of sustainability and specify how it simultaneously approaches and departs from the concept of circularity. Both terms CE and sustainability are increasingly gaining traction with academia, industry, and policymakers, but the similarities and differences between both concepts remain ambiguous and need to be explored (Geissdoerfer et al., 2017).
The terms "sustainability" and "sustainable development" are closely related and often used synonymously. The most quoted definition, as previously written, declares sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UN World Commission on Environment and Development, 1987).

Three different areas (also called dimensions or pillars) of sustainability have been identified, as one can observe in Figure 2, and, here, listed:

1. In *Environmental Sustainability,* ecological integrity is maintained, and all of Earth's environmental systems are kept in balance while natural resources within them are consumed by humans at a rate where they can replenish themselves.
2. In *Social Sustainability,* universal human rights and necessities are attainable by all people, who have access to enough resources to keep their families and communities healthy and secure. Healthy communities have just leaders who ensure personal, labor, and cultural rights are respected and all people are protected from discrimination.
3. In *Economic Sustainability,* human communities across the globe can maintain their independence and have access to the resources that they require, financial and other, to meet their needs. Economic systems are intact, and activities are available to everyone, such as secure sources of livelihood.

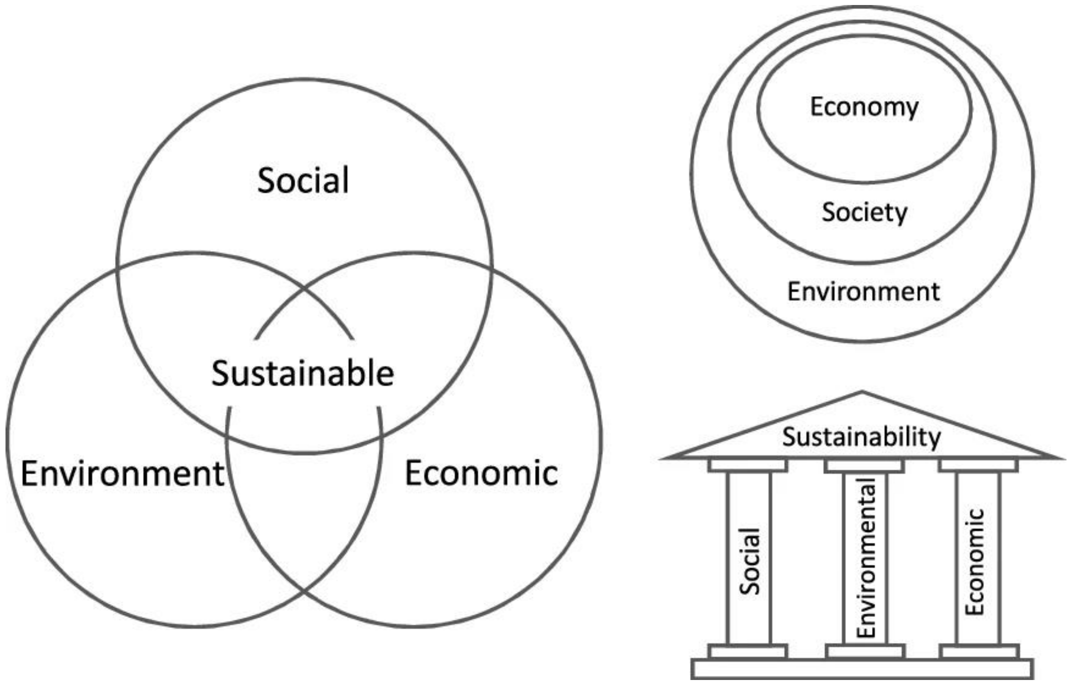


Figure 2 Left, a typical representation of sustainability as three intersecting circles. Right, alternative depictions: literal ‘pillars’ and concentric circles approach (Purvis et al., 2019).

In addition, a definition of sustainable production is provided. Sustainable production is the manufacturing of products and the creation of services, which respond to market needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants so as not to jeopardize the needs of further generations (Oslo Symposium of 1994).

In the literature, the strong relationship between CE and sustainability shows that CE research mainly addresses a limited number of environmental aspects (such as waste, resource use, and CO2 emissions), while other environmental and social aspects are given less attention. The most frequently used methods of sustainability assessment are material flow and life cycle analysis, the CE is mostly related to the environmental aspects, meanwhile sustainability is related to the 3 aspects shown in Figure 2 (Schöggl et al., 2020).

The relationship established between the concepts of sustainability and CE led us to believe that while all treatment options can impact a company's sustainability, only those that prioritize the recovery of product value are in line with the CE philosophy. This conclusion aligns with recent studies which suggest that CE can be seen as a means of achieving sustainable business practices, but not all circular systems are inherently more sustainable. This is because CE is primarily focused on environmental protection and may not always be the most appealing from an economic and social sustainability perspective (Alarcón et al., 2020).

Table 1 Similarity between the concepts of sustainability and the CE by (Geissdoerfer et al., 2017)

Similarities between sustainability and the Circular Economy
Intra and intergenerational commitments
More agency for the multiple and coexisting pathways of development
Global models
Integrating non-economic aspects into development
System change/design and innovation at the core
Multi-/interdisciplinary research field
The potential cost, risk, diversification, value co-creation opportunities
Cooperation of different stakeholders is necessary
Regulation and incentives as core implementation tools
The central role of private business, due to resources and capabilities
Business model innovation as a key to industry transformation
Technological solutions are important but often pose implementation problems

In summary, the CE and sustainability concepts share some similarities, such as a focus on environmental hazards, the importance of agency and public deliberation, a global perspective, and the need for cooperation between stakeholders as shown in Table 1. However, there are also several differences between the two concepts. The early stages of CE research mainly assumed that CE practices were beneficial for both the environment and the economy, but this has been increasingly challenged in recent years. The corporate perspective dominates the CE debate, while the consumer's perspective receives limited attention (Schöggl et al., 2020). The CE has more recently emerged than the concept of sustainability and is mainly motivated by the observation that resources could be better used in a closed-loop system, with primary benefits for the environment and implicit benefits for society. In contrast, sustainability is motivated by a wider range of past trajectories and is open-ended in terms of goals, with a focus on benefiting the environment, the economy, and society. The CE prioritizes the economic system, while sustainability is more holistic, treating the environment, economy, and society as equal and balanced. The CE places a clear emphasis on governments and companies, while the responsibilities are diffused in sustainability. The time frame for change is open-ended in sustainability and limited in the CE. Finally, the focus of the two concepts is different, with sustainability emphasizing interest alignment between stakeholders, while the CE prioritizes financial advantages for companies and environmental benefits (Geissdoerfer et al., 2017).

Circular Economy and Lean Manufacturing

After having introduced the differences between CE and sustainability, to better understand CE, it is important to link it with Lean Production (LP) as well due to the growing recognition of the economic and environmental benefits of this approach. LP is a philosophy and set of principles that aim to eliminate waste and increase efficiency in manufacturing and service operations (Manea, 2013). By applying lean principles to the CE, organizations can not only reduce their environmental impacts but also improve their competitiveness and financial performance. A literature review of the link between CE and LP can help to understand the synergies and potential trade-offs between these two approaches, as well as the conditions and practices that enable their successful integration. Such a review can also contribute to developing best practices and guidelines for implementing circular and lean initiatives in different sectors and contexts.

Different definitions are provided for LP, the first one divided the concept through three stages. In the first one, it was considered a set of tools (like Kanban); in the second one, a manufacturing method (like JIT); in the third, it is assumed to be a general management philosophy based on the reduction of waste and lead time (Koskela, 1992).
Another definition by Womack & Jones in 1996 considers LP as a strategy based on five key elements: *value*, *value flow, flow, pull,* and *perfection*. It aims at the elimination of waste, the satisfaction of customer needs, the generation of value and value flows, the striving for excellence, the guarantee of reliability in all production phases, and continuous improvement in all processes.
According to Sciortino et al., in 2009, the concept of LP is intended as lean transformation and means to do more with less. For the first time, besides the eight wastes (defects, excess processing, overproduction, waiting, inventory, transportation, motion, and non-utilized talent), energy is addressed as the ninth waste.

The CE has been defined as very close to Lean Manufacturing (LM), a production methodology that aims to minimize waste and optimize efficiency by identifying and eliminating non-value-added activities in the manufacturing process. As said, it is based on the idea of continuous improvement and the belief that even small efficiency improvements can significantly impact overall performance. LM techniques can be applied to a wide range of industries and are often used to increase productivity, reduce costs, and improve the quality of products or services. Some common LM tools and techniques include Value Stream Mapping, Kanban systems, and 5S (*sort, set in order, shine, standardize, sustain*) (Shahriar et al., 2022). CE is emerging as an advanced alternate model by designing environmentally integrated systems to balance the sustainable pillars coupled with industrial progression. CE involves the replication of lean systems with minimal or zero waste with highly optimized bundling of resources to foster natural cycles into production as well as consumption processes (Ghosh et al., 2022).

Defining CE as a concept aimed at creating a more sustainable and efficient economic system, where resources are kept in use for as long as possible, and waste is minimized. In a manufacturing context, CE principles can be applied in various ways, such as designing products that are easier to repair or recycle, optimizing processes to reduce waste and conserve resources, and engaging with suppliers and customers to promote sustainability (Ciliberto et al., 2021). This idea aligns with the LP, which also prioritizes waste reduction and efficiency in production processes.

Therefore, CE fundamentals are very linked with LP ones and maintain the long-term value of materials/products by reducing waste and further preserving resources by refurbishing or recycling, or reusing them into another product/raw material.

This relationship has been investigated by researchers to understand how companies and industrial systems might use Value Stream Mapping (VSM) as a tool to enhance sustainability and accelerate change toward CE (Hedlund et al., 2020). VSM was introduced in 1980 by Taiichi Ohno and Shigeo Shingo, as part of the Toyota Production System, through which the Japanese company has implemented a policy of reducing waste in production processes. VSM is a technique — developed from LM — that organizations use to create a visual guide of all the components necessary to deliver a product or service. It is composed of a set of activities and processes necessary for the realization of a product, starting from the supplier to the delivery of the finished product. Activities are divided into two groups: value-added activity and non-value-added activity.

The VSM objective is to identify and reduce any non-value-added activity (waste), highlighting the points of improvement of the process (G. Bruno, 2022). The research by Hedlund in 2020 aims at understanding how VSM can empower CE, and highlights that the product's value is considered through its use, maintenance, remanufacturing, and eventual recycling, allowing for a closed loop of resources. Closing the resources loop, as will be explained in the next paragraphs, is one of the most important actions for reaching CE. Indeed, the paper confirms VSM as a lean production tool that can help to promote sustainability and support the transition towards a CE.

Following, these are the most important ways in which lean manufacturing and the circular economy are related:

1. Lean manufacturing aims to eliminate waste and optimize efficiency in the production process, which aligns with the principles of the circular economy. By reducing waste and increasing resource efficiency, lean manufacturing can help to create a more circular system (Pawlik et al., 2021).
2. The principles of lean manufacturing, such as continuous improvement and maximizing value, can be applied to the design of products and systems to make them more compatible with the CE. For example, designing for durability, repairability, and recyclability can help to extend the life of products and materials (Ciliberto et al., 2021).
3. The incorporation of CE principles into Lean philosophy is crucial. Lewandowski's (2016) framework classifies sustainable production into four areas: business models and processes, asset and product lifecycle management, resource, and energy management, and enabling technologies. In 2021, Ciliberto et al. demonstrate the possibility of effectively applying CE principles and achieving sustainable development goals across all four areas.

Overall, LM and CE are both focused on improving resource efficiency, and reducing waste is one of the main concepts related to CE, and production tools, such as VSM, are useful to empower circularity during production processes.

Circular Economy and Linear Economy

What emerges from the literature review is the urgent necessity to transition from a Linear Economy (LE) to a Circular one (Michelini et al., 2017). The aim of transitioning from a linear to a CE is to move away from a model of resource consumption and waste generation, towards a more sustainable and efficient system of resource use. In addition, circular business models are increasingly viewed as a key driver for business competitiveness and sustainability (Bocken et al., 2016).

A LE is based on the traditional model of "*take, make, use, dispose of*" where resources are extracted, processed into products, used, and then discarded as waste. This can lead to resource depletion and environmental degradation, as well as waste and inefficiency (Lieder and Rashid, 2016).

A CE, as previously mentioned, is based on the principles of reusing, repairing, refurbishing, and recycling resources. It aims to keep materials and products in use for as long as possible and to extract the maximum value from them while they are in use. This can help to reduce waste, minimize environmental impact, and improve resource efficiency as highlighted in the previous Section.

The transition to a CE is often seen to address environmental and resource challenges and to create more sustainable and resilient economic systems (Rizos et al., 2016).
The starting point of this paragraph is the definition of CE that emphasizes the differences between the LE and the circular one by Sauvé et al., 2016. It must be specified that one of the hurdles that the CE faces is that it is usually more expensive to manufacture a durable, long-lasting good than an equivalent quick and disposable version. This is a public good problem: the benefits of producing less or non-durable goods are private while the environmental cost is public (Sauvé et al., 2016).

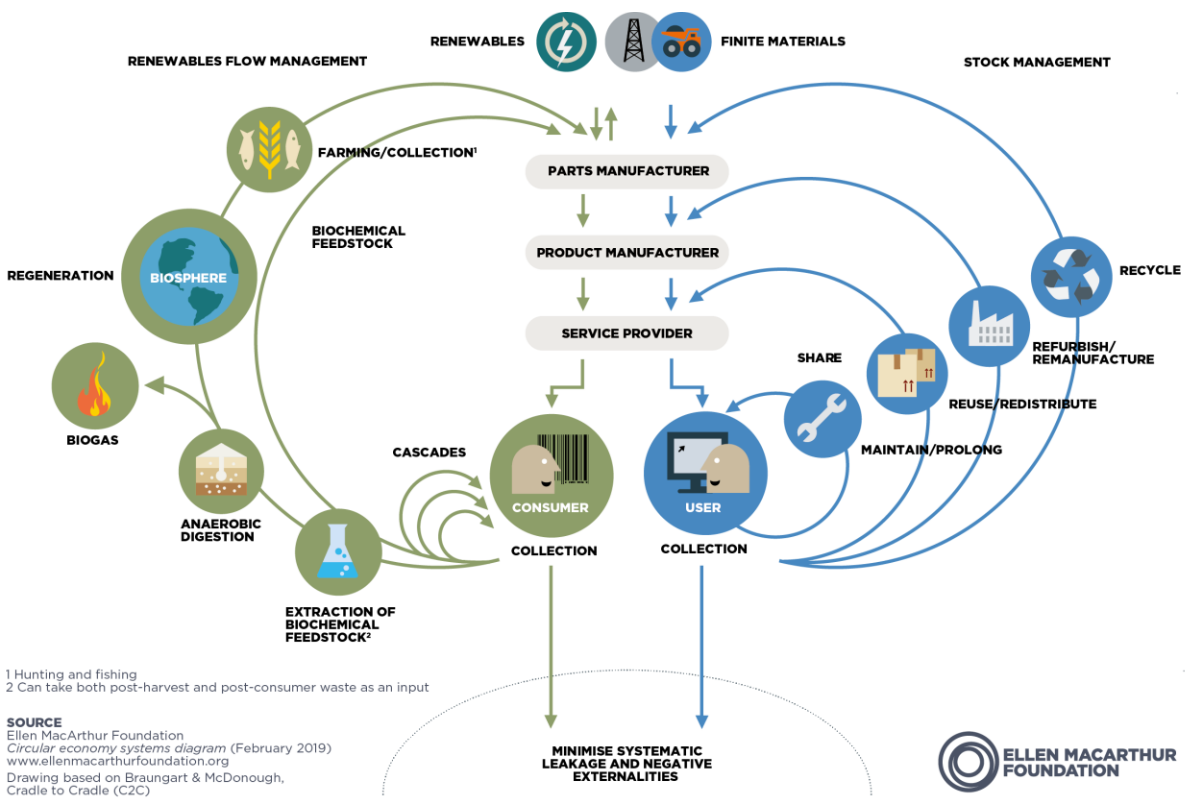


Figure 3 The Butterfly Diagram by Ellen Macarthur Foundation.

The CE system diagram, known as the Butterfly diagram, shown in Figure 3, illustrates the continuous flow of materials in a CE. There are two main cycles – the technical cycle and the biological cycle. In the technical cycle, the blue one, products and materials are kept in circulation through processes such as *reuse, repair, remanufacture,* and *recycling*. In the biological cycle, the green one, the nutrients from biodegradable materials are returned to the Earth to regenerate nature.

The left-hand side, the biological cycle of the CE, focuses on biodegradable materials that can safely return to the Earth, such as food and other natural resources. The central principle of the biological cycle is *regeneration*, where the focus is on improving the environment rather than just minimizing harm. Farmers may adopt regenerative agriculture practices to create positive outcomes for nature, such as healthy soils, increased biodiversity, improved air and water quality, and carbon storage. The organic waste from harvested and consumed food can be returned to the soil through composting and anaerobic digestion, which can produce biogas and soil amendment. Biogas can be used as a source of energy, and biorefineries can produce high-value chemical products from organic waste. The biological cycle makes use of materials already in the economy and returns biodegradable materials to the soil when they can no longer be used.

On the right-hand side of the Butterfly diagram is the technical cycle, relevant for products that are used rather than consumed, this passage describes the different stages in the technical cycle of a CE, where the focus is on maximizing the value of products and materials by keeping them in use, rather than letting them become waste. The different stages are sharing, maintenance, reuse, redistribution, refurbishing, and remanufacturing. These stages aim to keep products whole, increase their utilization, prolong their usable life, and restore their value. Each stage works best when products are designed for that stage, for example, by making products durable, modular, and recyclable. The passage also provides examples of businesses and platforms that are working to promote each stage, such as community tool libraries, car-sharing systems, reusable packaging, resale platforms, refurbishing companies, and the Right to Repair movement (Ellen Macarthur Foundation, 2019). The right-to-repair movement tries to address issues by proposing legislation obligating manufacturers to allow access to spare parts and repair tools at fair market prices and design devices to favor repair over replacement (Hatta, 2020).

In 2015, Ellen MacArthur Foundation and McKinsey & Company's work has been fundamental for understanding which are the product design and business model strategies for companies that want to move to a CE model.

To provide and develop a framework of strategies to guide designers and business strategists in the move from a linear to a CE, the terminology of slowing, closing, and narrowing resource loops must be introduced (Ellen MacArthur Foundation and McKinsey & Company).

1. *Slowing* resource loops: through the design of long-life goods and product-life extension, the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources. This can be achieved using durable materials, good-quality construction, and easy repairability. By slowing down the rate at which products are replaced, we can reduce the overall demand for new resources and help to conserve the planet's finite resources.

2. *Closing* resource loops refers to the practice of recycling and reusing materials, rather than discarding them. By recycling, we can turn used products and materials into new ones, closing the loop between the post-use phase and production. This helps to reduce the demand for new raw materials and can also reduce the amount of waste that ends up in landfills.

3. Resource efficiency, also known as "*narrowing* resource flows," refers to the practice of using fewer resources to produce a given product or service. This can be achieved using more efficient technologies, processes, and materials, as well as through the design of products that are more energy- and resource-efficient. By using fewer resources, we can reduce the environmental impact of production and consumption and help to ensure that the planet's resources are used in a more sustainable way.

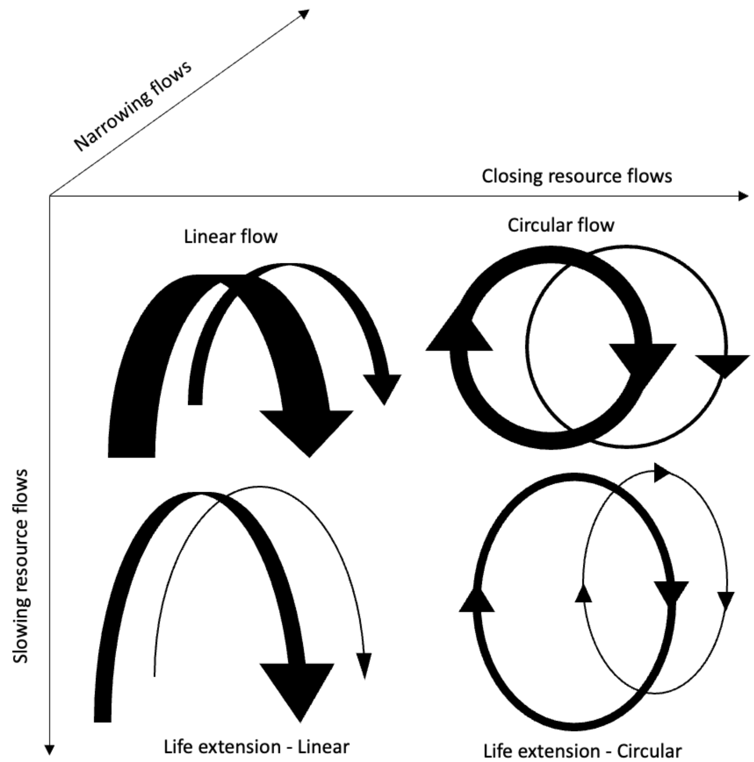


Figure 4 Categorization of linear and circular approaches for reducing resource use (Bocken et al., 2016).

Figure 4 represents what means to switch from a linear to a CE, changing the 3 variables first defined. All these variables are helpful in the transition to a CE as they help reduce demand for new resources and minimize waste. By slowing the flow of resources, closing resource loops, and using resources more efficiently, in fact, it is possible to create a more sustainable and regenerative economic system that is better able to meet the needs of present and future generations.

Transitioning from a linear to a CE can be a complex and challenging process, as it requires significant changes to the way that we produce and dispose of goods and resources (Michelini et al., 2017).

The focus of CE transitions is on changing the way natural resources and materials are utilized, from a linear to a circular manner. There are three types of CE transitions based on the role of technology in product chains:

1. CE transitions are driven by the emergence of new, revolutionary technology (radical innovation in core technology). In this type, a change in socio-institutional norms is needed to establish the technology's place in society.
2. CE transitions are led by socio-institutional changes, with technology playing a minor or no role (incremental innovation in core technology).
3. CE transitions involve a central socio-institutional change but are facilitated by enabling technology, such as the transition to the sharing economy. In this case, a

transition from owning a product to purchasing its services primarily involves a socio-institutional change, but information technology is necessary to connect service providers and users (Lambrechts et al., 2021).

The article states that coordination failure can be a challenge in the transition to a CE, as it requires economic actors to work together and coordinate their efforts to achieve common goals. Coordination failure can occur when there is a lack of communication, trust, or shared incentives among economic actors, which can hinder the development of joint solutions and the implementation of circular practices. There are a few ways that coordination failure can be addressed in the context of a CE transition: developing clear communication channels and fostering open and transparent communication between economic actors, encouraging collaboration and partnerships between economic actors, including using platform business models.

Furthermore, the "10 Rs", shown in Figure 5, are a set of strategies that can be used to promote sustainability and reduce waste by encouraging resource conservation and reuse, these describe the essence of CE. As represented, Potting et al. developed a framework that categorizes strategies for achieving circularity in order of increasing power, with R9 being the most powerful and R0 being the least powerful (Potting et al., 2017). Even if the authors note that this hierarchy should not be considered a strict rule, as there may be exceptions and secondary effects that can affect the effectiveness of these strategies, the hierarchy must be considered with caution and used as a general guide when evaluating CE strategies. As shown in Figure 5, R0, R1, and R2 strategies decrease the utilization of natural resources and materials applied in a product chain by fewer products being needed for delivering the same function. These three strategies are related to the Design Phase, strategies from R3 to R7 are related to consumption aspects of the products, and the latter two (Recycle and Recovery) are related to how to return the product after its life cycle come to an end.

Circular Economy ↑	Smarter product use and manufacture	**R0**	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
		R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
	Extend lifespan of product and its parts	**R3**	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
		R4	Repair	Repair and maintenance of defective product so it can be used with its original function
		R5	Refurbish	Restore an old product and bring it up to date
		R6	Remanufacture	Use parts of discarded product in a new product with the same function
		R7	Repurpose	Use discarded products or its part in a new product with a different function
	Useful application of materials	**R8**	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
Linear Economy		**R9**	Recovery	Incineration of material with energy recovery

Figure 5 10 Rs strategies adapted from Morseletto et al., a short description of each concept is given on the left side of the figure. The 10 Rs are benchmarked and divided into 3 macro-categories: from R0 to R2, from R3 to R7, and from R8 to R9.

Another useful tool for helping organizations to understand the circularity of their products, systems, and business models, and to identify opportunities for improving their sustainability and reducing their environmental impact is the ReSOLVE framework.

Developed by McKinsey in 2016, the framework takes the core principles of circularity and applies them to six actions as follows: Restore/REgenerate, Share, Optimize, Loop, Virtualize and Exchange strategies (see Table 2). The framework based its Circular Business Model (CBM) on six classified criteria, which are six business actions implementing the principles of CE. These business actions are considered parts of the ReSOLVE framework. To transition from the current trajectory to a circular one, European economies and companies must undertake six business actions: regenerate, share, optimize, loop, virtualize, and exchange – the ReSOLVE framework.

Table 2 ReSOLVE framework by McKinsey & Company in 2016. Left side: the seven criteria highlighted in the paper. On the right side, some action examples that could empower CE are provided.

Circularity Actions	**Examples**
REGENERATE	•Shift to renewable energy and materials •Reclaim, retain, and restore the health of ecosystems •Return recovered biological resources to the biosphere

SHARE	•Share assets (example cars, rooms, appliances) •Reuse/secondhand •Prolong life through maintenance, design for durability, upgradability, etc.
OPTIMIZE	•Increase performance/efficiency of the product •Remove waste in production and supply chain •Leverage big data, automation, remote sensing and steering
LOOP	•Remanufacture products or components •Digest anaerobically •Recycle materials
VIRTUALISE	•Dematerialize directly (ex. books, CDs, DVDs, travel) •Dematerialize indirectly (ex. online shopping)
EXCHANGE	•Replace old with advanced non-renewable materials •Apply new technologies (ex 3D printing) •Choose new product/service (ex. multimodal transport)

The ReSOLVE framework is designed to be flexible and adaptable and can be used in a variety of different contexts and sectors. It is typically used to identify and prioritize circular opportunities, and to develop strategies for implementing circular practices. It is important to note that these technological advances not necessarily will reduce costs, surely many might improve performance instead. Moreover, transitioning is not an immediate process; it takes time to make a difference (McKinsey, 2016).

Firms can adopt different strategies to innovate towards CE to manage product, component, material, and energy flows. These strategies include: *narrowing*, *slowing*, *closing*, *regenerating*, and i*nforming,* shown in Table 3. The first 3 strategies, "narrowing", "slowing", and "closing", have been previously proposed while "regenerating" has been added to emphasize the importance of minimizing the use of toxic substances and increasing the use of renewable materials and energy (Konietzko et al., 2020). The final strategy, "informing", has been included to highlight the importance of information technology in enabling a CE. Each strategy can be broken down into innovation principles which may require a product, business model, or ecosystem perspective.

Table 3 Circular strategies and definitions from (Konietzko et al., 2020).

Strategy	Definition
Narrow	Use less
Slow	Use longer
Close	Use again
Regenerate	Make clean
Informing	Use information technology

Circular Economy and Life Cycle Assessment

The adoption of CE principles has gained significant attention in recent years as a means of achieving more sustainable and resource-efficient systems. As previously mentioned, one of the key components of a CE is the minimization of waste through the continual use of resources. Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts of a product or system throughout its entire life cycle, from the extraction of raw materials to its disposal. The integration of LCA and CE can provide a comprehensive framework for designing sustainable products and systems, as LCA can identify areas where circularity can be improved, while CE can help minimize environmental impacts by reducing waste and promoting the efficient use of resources. In this Section, we explore the relationship between LCA and CE and their joint application toward achieving sustainable development.

First of all, it is necessary to contextualize LCA in a broader context, the one of Product Life Management (PLM). PLM refers to the process of managing a product from its conception to its eventual retirement, including design, development, manufacturing, marketing, and disposal. The goal is to optimize the product's economic, environmental, and social performance throughout its entire life cycle. Considering this definition, LCA is a tool used in PLM to evaluate the environmental impact of a product throughout its life cycle. It considers all stages of the product's life, including the extraction of raw materials, production, use, and end-of-life disposal.

The first studies to look at life cycle aspects of products and materials date from the late sixties and early seventies and focused on issues such as energy efficiency, the consumption of raw materials, and, to some extent, waste disposal. In 1969, for example, the Coca-Cola Company funded a study to compare resource consumption and environmental releases associated with beverage containers.

The LCA model typically includes the various life cycle phases of a technical system, such as raw material extraction, production, transportation, manufacturing, use, and disposal. The purpose of the LCA model is to identify and quantify the environmental impacts associated with each of these phases, including factors such as resource use and pollutant emissions. By allocating these environmental burdens to the relevant life cycle stages, the LCA model provides a comprehensive assessment of the environmental impacts of the entire system (Finnveden et al., 2009). The LCA process refers to the actual steps taken to conduct a LCA, which typically involves defining the scope of the study, collecting, and analyzing data, interpreting the results, and communicating the findings to stakeholders. The framework of the LCA process is shown in Figure 6 below.

The framework for conducting and reporting LCA studies is defined by the internationally agreed standards ISO 14040 - 14043 developed by the International Organization for Standardizations (ISO). The LCA process is divided into four iterative phases (ISO 14040, 1997): goal and scope definition, inventory analysis, impact assessment, and interpretation as represented in Figure 6.

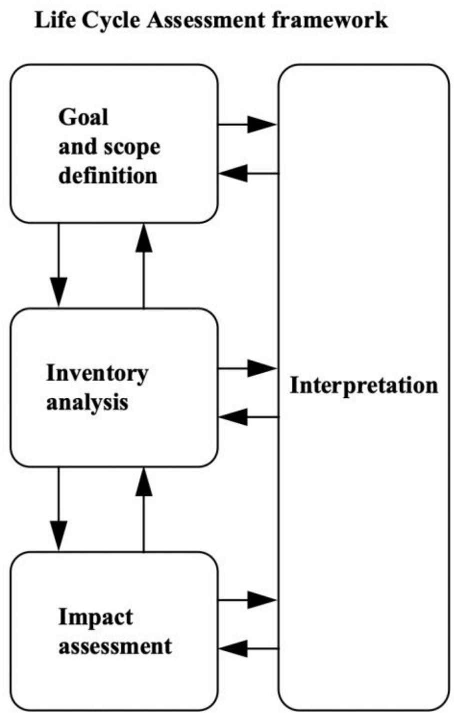


Figure 6 Phases of the LCA process according to ISO 14040 in 1997.

The goal and scope of an LCA study should be well-defined at the beginning and consistent with the intended application. The scope should be detailed enough to address the stated goal and may need to be modified as additional information is collected during the iterative LCA process. Different types of LCA studies may have varying goal and scope definitions, which are important to consider when identifying the technical system, defining the system boundary, and allocating environmental burdens. The level of detail and quality of inventory data are critical considerations that strongly influence the cost of the study. A proper definition of the functional unit is important when comparing different technical systems and can be used as the allocation basis for calculating environmental impacts. The use of allocation principles, such as when more than one product is produced in the same process, should also be considered.

LCA involves the evaluation of some aspects - often the environmental aspects - of a product system through all stages of its life cycle. Sometimes also called “life cycle analysis”, “life cycle approach”, “cradle to grave analysis” or “eco balance”, it represents a rapidly emerging family of tools and techniques designed to help in environmental management and, longer term, in sustainable development. As an important tool in environmental management, policy, and planning, LCA provides information about the environmental impact of products and services associated with an organization and is useful in making decisions that require comparing environmental outcomes. LCA can be extended through tools such as Multi-Criteria Assessment, where quantitative and qualitative information is ranked and assessed across different environmental criteria. It can be incorporated into systematic tools to assess, monitor, document, manage, and maintain environmental performance, as well as environmental reporting systems and initiatives. LCA is also used in various applications such as eco-footprint and related calculators, advisory program information, and community engagement and behavior change tools. The effectiveness of LCA, however, depends on the modeler and the quality of the data and assumptions used in the case of (Horne et al., 2009).

LCA is often used to determine the best-performing product, service, or other solution, at a given point in time, in terms of specific environmental impacts, such as carbon emissions. However, it has some limitations (Ellen Macarthur Foundation, 2015).

1. In fact, when transitioning to a CE, it is important to keep in mind that LCA can sometimes prioritize short-term individual gains over long-term collective ones. LCA may point towards quick fixes based on the current system rather than promoting systemic change. For example, in the past, a LCA suggested improving the efficiencies of petrol cars rather than investing in developing electric vehicle technology and renewable energy production.
2. A second limitation is that LCA can only measure quantifiable metrics, such as carbon emissions, and may not consider harder-to-measure impacts like plastic in the environment or the long-term effects of landfill runoff. This limitation can lead to decisions being weighed more heavily towards measurable metrics, potentially overlooking important impacts. For example, assessing the environmental benefits of reuse models for plastic packaging versus single-use plastic disposal can be challenging for LCA, as landfill may be viewed as a form of "carbon storage" from a carbon perspective.
3. The third limit is that LCA only measures what is defined within its boundaries, ignoring anything outside of them. Furthermore, the reliability of the data and assumptions made can significantly impact the results. Different studies can arrive at different conclusions due to various factors such as data sources, system boundaries, and the expertise of the authors as well. It is essential to consider the quality and reliability of the data and the assumptions made when interpreting the results of an LCA, otherwise, the solution is given LCA.

Although the limitations that LCA has, in a CE transition, it can be used to identify areas of improvement, test against changing external factors, compare similar solutions, and be used in later stages of innovation when there is reliable input data. Care should be taken when using LCA in the early stages of an innovation process.

In summary, LCA is a valuable tool for assessing the environmental impact of products throughout their entire life cycle. By identifying areas where improvements can be made, LCA can guide decision-making to optimize a product's environmental performance. Furthermore, LCA is closely related to the concept of CE which emphasizes the need to design products with their entire life cycle in mind, including end-of-life disposal. By incorporating LCA into product design and management, companies can better understand and reduce the environmental impact of their products, while also supporting the transition toward a more sustainable, CE.

3

STATE OF THE ART

Introduction to the Literature Review

After having presented the CE definition and highlighted the importance of this topic, this literature review aims to examine the current state of research on different specific concepts and explore their interactions with one another. The literature review has been conducted by dividing the whole materials into three macro-categories to define the scope and hypothesis of the research and deeper understand the relationship between the Circular Economy (CE), Additive Manufacturing (AM), and Early Stages of Design (EDS). These concepts have been chosen due to their relevance to the field of study proposed in this thesis project and the potential for further investigation. The review will provide a summary of each concept's key findings and an analysis of their implications for future research. By synthesizing the existing research, this review will aim to contribute to a greater understanding of these concepts and their relationship to one another.

The literature review was conducted mostly in July, September, and October 2022 and has been finished at the end of the thesis project. The aim of this State of the Art is to find the common concepts and the past and possible future applications of CE in the EDS of AM processes. After that, more papers have been reviewed to conduct the research work and decide which methodology to implement.

At this stage, Scopus's databases (Baas et al., 2020) were used to find academic publications related to the research terms "*Circular Economy*", "*Additive Manufacturing*" and "*Early Stages of Design*"/ "*Early Design Stages*". The search, presented in Figure 7, included title, abstract, and keywords and was limited to works published within the past 20 years. Moreover, other keywords shown in Table 4 have been used to find articles related to more than one of the above terms. The term "*eco-design*" has been added to the search string referring to a more general word for "*Early Design Stages*" linked with "*Circular Economy*".

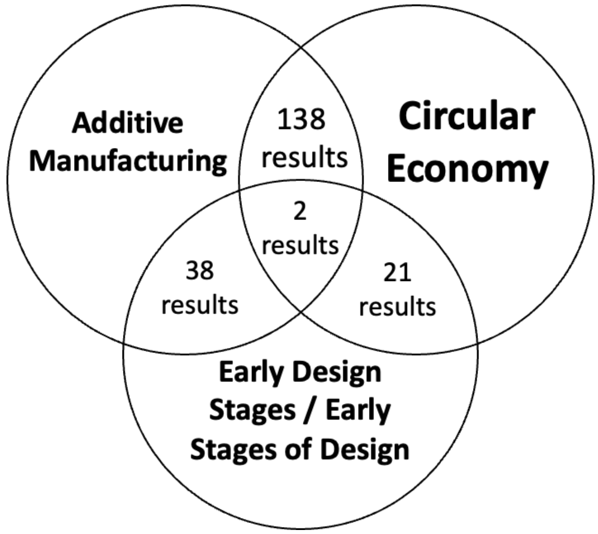


Figure 7 Most important keywords for Scopus' research.

Table 4 Additional research queries used to conduct the State of the Art.

Other research queries on Scopus	Queries' results
TITLE-ABS-KEY ("eco-design") AND TITLE-ABS-KEY ("circular economy")	171
TITLE-ABS-KEY ("additive manufacturing") AND TITLE-ABS-KEY ("lean production")	14
TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY ("lean production")	26
TITLE-ABS-KEY ("design by additive manufacturing")	6
TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY ("life cycle assessment") AND TITLE-ABS-KEY ("additive manufacturing")	10

Challenges for promoting Circular Economy in the Early Design Stage

In the context of CE, the EDS plays a crucial role in achieving a CE, as design decisions have a significant impact on the entire product life cycle, from the extraction of raw materials to end-of-life disposal. However, integrating circular principles into the EDS is not an easy task, and there are several challenges that need to be overcome to promote CE effectively. This chapter aims to explore these challenges, focusing on the barriers that hinder the application of circular principles in the EDS and the strategies that can be used to overcome them.

The Early Stages of Design (EDS) encompass "project definition and planning," research and validation of the concept, and architectural design up to the preliminary layout creation (Peng et al., 2018b). In terms of production stages, one of the hurdles that CE faces is that it is usually more expensive to manufacture a durable long-lasting good than an equivalent quick

and disposable version. This is a public good problem: the benefits of producing less or non-durable goods are private, while the environmental cost is public (Rödl et al., 2022).
As it has been declared from the strategies above presented, the decisions taken in the EDS of production of a product are very important in terms of sustainability. In fact, to reach a proper circular loop and apply CE strategies, it is fundamental to pay attention to the early stages of product development design.

This literature review first focused on the link between CE and EDS. As represented at the top of Figure 8, the first publication was in 2017 and the number of publications has reached a peak in 2020. As it is shown on the right side of Figure 8, most of the papers are articles and, as shown at the bottom of the same figure, the countries more active in publishing these papers are Sweden, Italy, and the UK. In a second moment, the research has been expanded to “eco-design” and “CE”. In Figure 9, it is possible to see that the number of papers is increasing from 2016 until nowadays and that the number of resulting papers is higher than the results of research in Figure 8. This information can be justified considering that eco-design is a concept strictly related to CE.

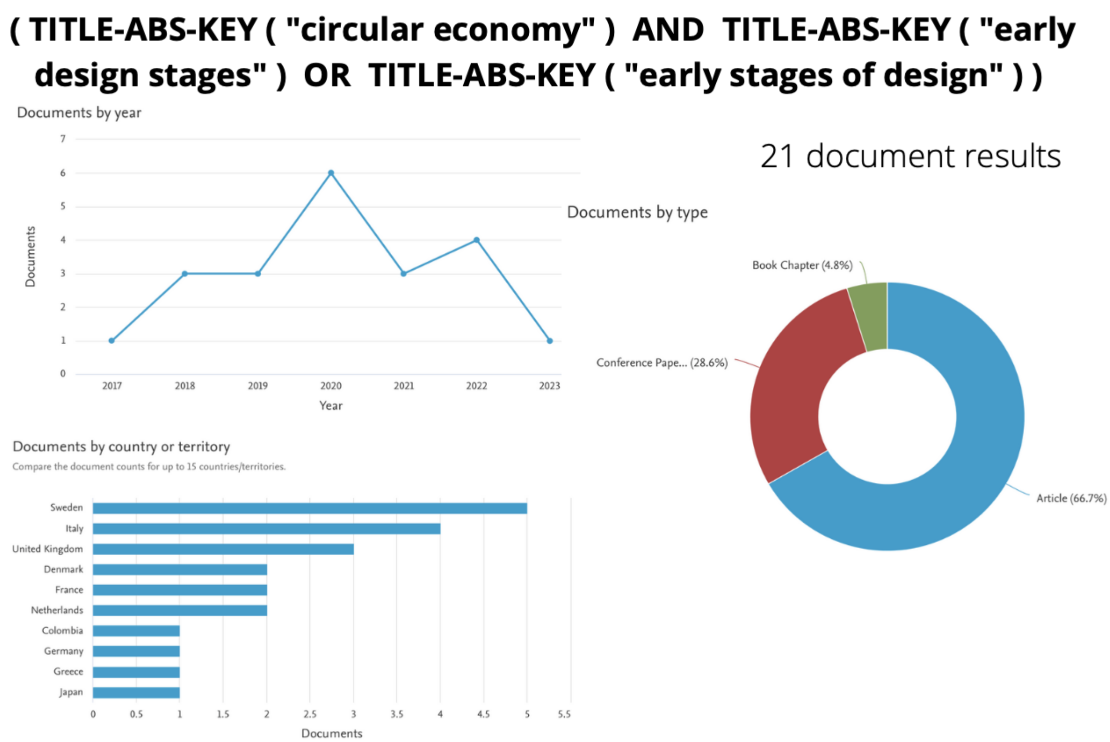


Figure 8 Results of “Circular Economy” and “Early Design Stages” research on Scopus.

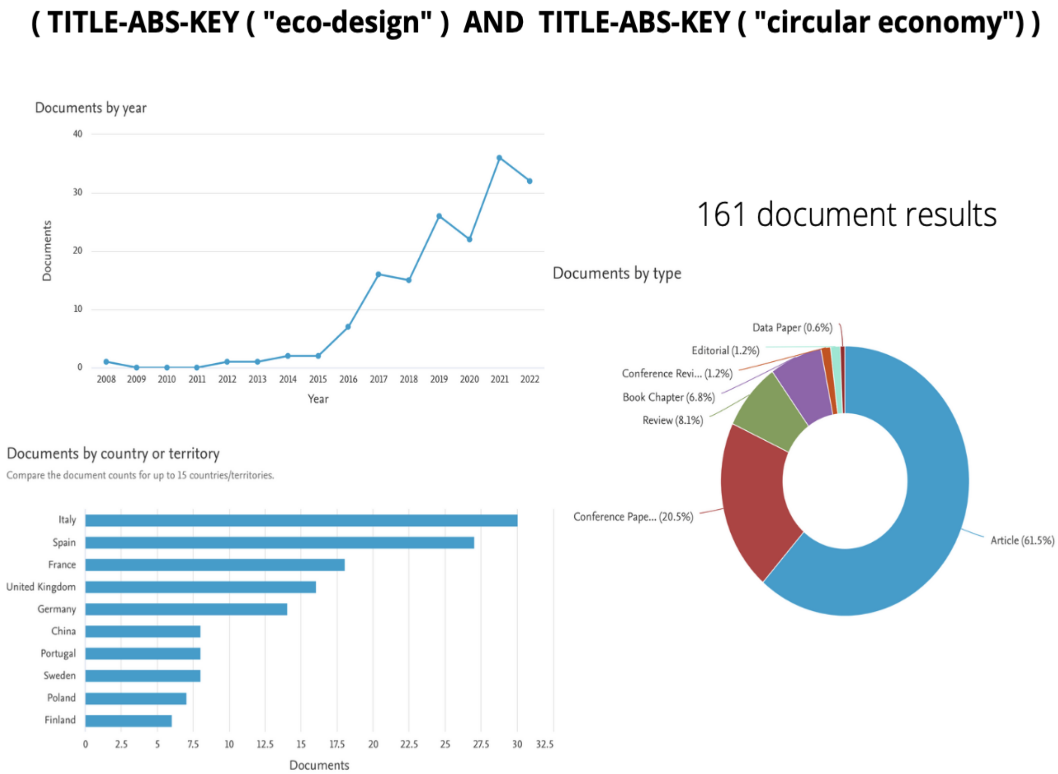


Figure 9 Results of "Circular Economy" and "Eco-design" research on Scopus.

Firstly, it is fundamental to define how to conduct the design process, Pahl et Beitz, in 1966, in their 'systematic approach', generally seen as a prescriptive model of designing based on observations of professional design practice, has presented three phases:

• At first, the *conceptual design* phase involves drafting functional descriptions, drawings, and block diagrams, defining high-level lists of components and modules, and comparing and selecting alternative solutions.

• Secondly, the *embodiment design,* in which components are defined at the level of preliminary technical drawings, while a preliminary selection is made for their materials and manufacturing processes. In this phase, the product's Bill of Materials (BoM) is defined in greater detail.

• Finally, the *detailed design* copes with the dimensioning of the previous results, technical validation through extensive engineering calculations, and detailing all the information required to make the product.

In the design process, the first phase, creativity plays a significant role in the conceptual phase the most, but its involvement decreases as the design progresses to the embodiment and detailed phases. In the beginning, there is limited, unstructured information available, mainly in the form of broad product descriptions. However, as the design advances, the amount of information grows and becomes more organized, with a focus on the product's structural layout. In the final detailed design phase, there is a substantial increase in information (Cantamessa and Montagna, 2016).

Furthermore, it is crucial to incorporate CE considerations early in the product design process as once the specifications are set, only minor modifications can typically be made. This is because once resources, infrastructures, and processes have been dedicated to a specific design, making alterations becomes challenging (Ellen MacArthur Foundation, 2015). In fact, as the design becomes more solidified and the product moves closer to production, it becomes more expensive to make changes, because more resources have been invested in the product and the changes may require more extensive rework. Additionally, making changes later in the development process may require updating product documentation and retraining personnel, which can also increase the cost of the Engineering Change Order (ECO).

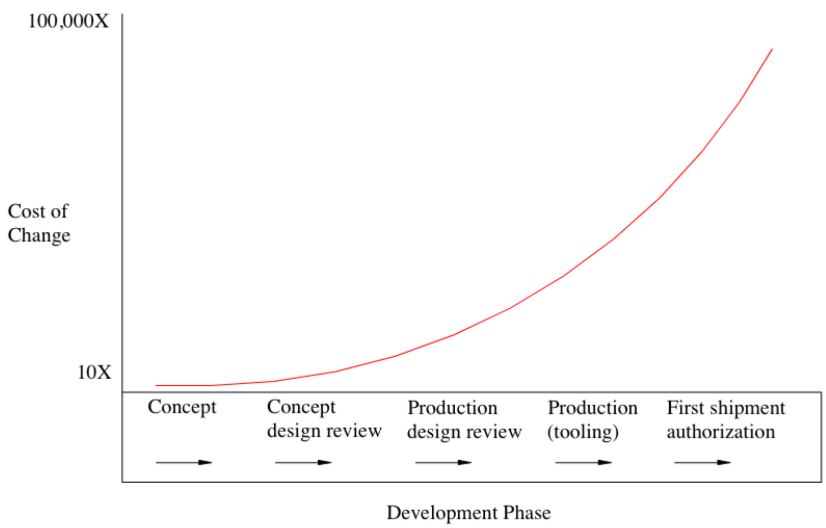


Figure 10 Cost of design changes in relation to the product development phase (Cantamessa and Montagna, 2016). In the plot, one can observe that the cost of change is a function of the development phase: in each following phase, the cost grows exponentially. It implies that the cost is exponentially lower during the early stages of production.

This economic idea is commonly represented using a general product development cycle and cost of ECO graph. As represented in Figure 10, the cycle typically includes five stages: concept, design review, production design review, production, and shipment approval. As a product moves through these stages, the costs linked to ECOs rapidly escalate. For instance, an ECO made during the conceptual phase with a cost of 10X could end up costing more than 50,000X if made during the production phase, which is later in the process. This highlights the importance of making decisions early in the product life cycle as a viable strategy for avoiding costly late-phase changes (Cantamessa and Montagna, 2016).

For companies, taking care of sustainability is becoming mandatory to remain competitive in the market. In this sense, the approach of eco-design described as ‘the development of products by applying environmental criteria aimed at the reduction of the environmental impacts along the stages of the product life cycle', is a strategy to improve the sustainability of a product in the design phase (Folkestad, 2001).

The concept of Design for a CE underscores the significance of material cycles that are both high in value and quality, making it a crucial area of focus for sustainable product design and development. This new area of research within sustainable design focuses on extending the product's life and ensuring the complete recovery of products and materials through a hierarchy of recovery strategies. This approach guarantees product integrity while promoting high-value and high-quality material cycles. In essence, Design for a CE provides a new perspective on the importance of material cycles and their impact on the sustainability of the product. The growing emphasis on this approach highlights the need for sustainable and circular product design and development practices (Babbitt et al., 2021).

Manufacturing companies need to prioritize sustainability to stay competitive in the market (Soosay et al., 2016). One approach they can take is eco-design, which is the process of designing products with the goal of reducing their environmental impact throughout their entire lifecycle. This approach can be used as a strategy to improve the sustainability of a product during the EDS (Folkestad, 2001). Design for CE has recently come into focus as a new research area in the wider field of sustainable design (Ceschin and Gaziulusoy, 2016). Product life extension and complete recovery of products and materials form essential elements of this approach, Design for CE highlights the importance of high-value and high-quality material cycles.

In conclusion, the EDS is a critical phase in achieving a CE and integrating circular principles into this stage is crucial to ensuring the sustainability of a product. Design for CE, with its focus on material cycles that are high in value and quality, provides a new perspective on sustainable product design and development practices. However, there are several challenges that need to be addressed to promote CE effectively in the EDS. By understanding these challenges and implementing appropriate strategies to overcome them, manufacturing companies can design more sustainable and circular products that meet the growing demand for environmentally friendly products and stay competitive in the market. The efforts made in the EDS to promote circularity will have far-reaching positive impacts on the environment and society, making it a crucial area for future research and innovation.

Additive Manufacturing

Additive Manufacturing (AM) is a rapidly growing and highly promising manufacturing technology that has attracted significant attention in recent years. AM, also known as 3D printing, is a fast-developing collection of production techniques that enable new manufacturing paradigms. Products are manufactured through a digital and additive process in contrast to conventional production methods. This additive and digital nature enables, for instance, on-demand production of spare parts for repair or avoids material losses when compared to subtractive technologies such as milling (Sauerwein et al., 2019). These aspects may also offer new opportunities when designing products for the CE.

AM is strongly related to CE and in fact, it is seen as "a powerful enabler of CE which aims at reducing resource consumption while boosting business opportunities" (Kravchenko et al., 2020). AM has revolutionized the way products are designed and produced, offering a range of benefits such as increased design flexibility, reduced material waste, and shorter lead times. In this chapter, we will explore the State of the Art in AM, its potential benefits, and the challenges that must be addressed to fully realize its potential for sustainable manufacturing.

3D printing has expanded beyond laboratory use for creating prototypes and has entered the manufacturing industry. A variety of substances such as liquids, powders, solid bars, and sheets can be printed through the solidification of successive layers using methods such as extruding, fusion, sintering, and polymerization. This technology has been used to create complex and high-quality structures with finer details and resolution compared to conventional manufacturing methods. Key advantages of 3D printing include reduced time, scalability, the ability to mass produce complex items, improved microstructure, and mechanical properties. The most used technology in 3D printing is "Fused Deposition Modeling" (FDM), which uses polymeric filamentous materials. Other techniques used include Selective Laser Sintering (SLS), Selective Laser Melting (SLM), liquid binding, contour crafting, inkjet printing, stereolithography, Direct Energy Deposition (DED), Laminated Object Manufacturing (LOM), vat photo-polymerization, and Powder Bed Fusion (PBF), each, as shown in Table 5, with its own advantages and disadvantages and targeted applications (Ahmed, 2023).

Table 5 A summary of materials, applications, benefits and drawbacks of the main methods of additive manufacturing (Ngo et al., 2018). The first column states the different methods of the AM. The second reports the materials used in each method. The third and the last ones outline the benefits and the drawbacks of each method.

Methods	Materials	Benefits	Drawbacks
FDM	Continues filaments of thermoplastic polymers	Low cost High speed	Weak mechanical properties Limited materials
SLS, SLM, 3DP	Compacted fine powders Metals, alloys, and limited polymers (SLS or SLM) ceramic and polymers (3DP)	Fine resolution High quality	Slow printing Expensive High porosity in the binder method (3DP)
Inkjet printing	A concentrated dispersion of particles in a liquid	Ability to print large structures	High workability in terms of time
DED	Metals and alloys in the form of powder or wire	Excellent mechanical properties	Low surface quality Need for a dense support structure Limitation

	Ceramics and polymers		in printing complex shapes with fine details
LOM	Polymer composites Ceramics Paper Metal-filled tapes Metal rolls	Reduced manufacturing time and cost A vast range of materials Excellent for manufacturing of larger structures	Inferior surface quality Limitation in manufacturing of complex shapes

As highlighted by Markou, in 2019, the opportunities of AM for sustainable manufacturing are:

- Reduction of the overall consumed resources because of the additive process.
- Waste reduction, due to less produced models.
- Waste up-cycling.
- Re-localization of production and shorter supply chains, lead to impact reduction due to logistics.

The literature describes circular design strategies which encapsulate some of the identified sustainable design strategies for AM, according to (Sauerwein et al., 2019).

1. **Design for attachment and trust**: the intention is to create products that will be loved, liked, or trusted longer. The potential contribution of AM to this strategy is discussed above.
2. **Design for reliability and durability**: the goal is to define optimum product reliability and durability. Products should operate throughout a specified period without experiencing failure when maintained properly.
3. **Design for ease of maintenance and repair**: products stay in a good condition by facilitating repair and replacement of broken parts. The potential contribution of AM to this strategy is discussed above.
4. **Design for upgradability and adaptability:** products should incorporate options to be expanded and modified to continue being useful under changing conditions, and to improve quality, value, effectiveness, and performance.
5. **Design for standardization and compatibility**: this strategy aims to create products with parts that fit other products as well as to facilitate intergenerational modularity.
6. **Design for disassembly and reassembly**: the aim is to ensure that products and parts can be separated and reassembled easily. This strategy can be applied to increase future rates of material and component reuse.
7. **Design for recyclability**: products should support their material recovery to establish continuous flows of resources. Recycled materials with equivalent properties must be obtained".

Additive Manufacturing and Circular Economy

Smart technologies, including AM, are increasingly recognized as key enablers for CE. This subchapter will explore in deeper the State of the Art in AM focusing on its potential for promoting CE principles, and the challenges that must be addressed to fully realize its potential for circularity.

Nowadays, in the literature, there is a lack of consensus on what constitutes smart technology, leading to conceptual ambiguity. Smart technology encompasses various advancements in information technology, with the goal of transforming the educational environment through digital means (Vinogradova et al., 2020). The development of smart technology was shaped by the transition from Web 2.0 to Web 3.0, as well as the rise of social media platforms and the government has categorized the most significant smart technologies under Industry Plan 4.0, which includes nine categories: advanced manufacturing solutions, additive manufacturing, augmented reality, simulation, horizontal/vertical integration, industrial internet, cloud, cyber-security, and big data and analytics. Smart technologies such as AM systems are used to monitor and control smart production lines and to improve operational flexibility, operational efficiency, and operational effectiveness in order to enhance operational performance, in line with CE principles. It has been studied that AM can improve supply chain flexibility and supply chain performance (Delic and Eyers, 2020). Further, to emphasize the importance of AM, it has been also demonstrated that using 10 R-based approaches such as Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover can provide options for cleaner production and can help firms achieve a competitive edge over their competitors (Kirchherr et al., 2017). In fact, the advanced manufacturing technology of AM and prototyping can help immensely in 10R manufacturing operations and 10R advanced manufacturing capabilities have a positive influence on sustainable development (Bag et al., 2021).

Therefore, digital and smart technologies such as AM can be used to allay uncertainties in 10R manufacturing operations. Digital technologies can be used to monitor and optimize production processes, reduce downtime, improve quality and efficiency, and enhance communication and collaboration among different stakeholders in the manufacturing ecosystem, including suppliers, customers, and service providers. This can help to reduce uncertainty by improving visibility, responsiveness, and agility in the supply chain (Zhang et al., 2022).

It is clear at this point that AM is seen as a powerful enabler of CE, aiming at reducing resource consumption while boosting business opportunities. In fact, AM has a great potential in supporting a variety of CE strategies, ranging from providing recycled materials to original manufacturing, repair, and remanufacturing activities, to recycling of materials at the end of life (Kravchenko et al., 2020). Indeed, the following Table 6 provides deeper details of these strong relations.

CE strategies	**AM enabling context**	**Beneficial opportunity of AM for CE**
Reinvent the paradigm	- Personalized products to build customer attachment - Adding functions to the Product	- Product attachment might encourage customers to keep the product for longer - Multifunctionality can eliminate the need for extra products
Rethink & Reconfigure business	Stimulation of new value propositions (e.g., subscription model to offer customized products and their part replacement and repair)	- Customization and customer co-creation allows to build stronger relationship and ensure customer retention and satisfaction - Quicker response to customer needs
Reduce, Restore & Avoid impacts in Raw Material and Sourcing	- Utilization of (local) recycled material as a feedstock for 3DP to produce new products - Mono-materiality	- Reduced cost of transport and material procurement - Reliance on local materials - More control over material quality and quantity (mono-material products to ease potential recycling) - Utilization of bio-based materials
Reduce, Restore & Avoid impacts in Manufacturing	- Production to order (flexible, on-demand, make-to-order MTO) - Distributed (local) manufacturing - High-precision production and no additional machining tools - Modularity	- Elimination of surplus attributed to conventional Production to stock - Local manufacturing - Building economy of scope rather than of scale - Empowerment of local communities and smaller businesses - Shorter supply chains and reduced costs - Reduced material losses and scrap - Faster 3DP machine set up and reduced time response Late-stage customization to reduce excess inventory
Upgrade	Adding extra elements or re-styling	- Adding desirable features to prolong product use and operation and increasing customer desirability
Repair and Maintenance	Rebuilding broken parts	- Flexible (value chain independent) operation - Instant Production of spare parts and rebuilding the broken part

		- Reduction of packaging material and costs - Proximity to the customer might encourage them to repair
Re-use		
Refurbish	Refurbishing of products	Reproduction of failed parts
Remanufacture	- Remanufacture of components - High-precision rebuilding and no additional machining tools - Reverse Engineering	- Flexible (value chain independent) remanufacturing operation - Reduction of packaging material and costs -Reproduction of old parts
Repurpose	Adjusting parts	- Prolonging use of parts in another use contexts
Recycle	Distributed recycling of materials	- Local (decentralized) recovery of waste - Reduction of transport costs

Table 6 The relationship between CE and AM (Kravchenko et al.,2020). The first column itemizes the different CE strategies. In the middle part, one can read the corresponding AM-enabling contexts. The last column highlights the beneficial opportunity of the AM for a CE.

Table 6 highlights all the beneficial opportunities of AM and CE defined by the literature until now, showing that CE strategies can benefit from AM enabling contexts to create new opportunities such as reinventing the paradigm through personalized products, stronger customer attachment, rethinking and reconfiguring business for new value propositions, or using local recycled materials and bio-based materials in AM to reduce costs and improve control over material quality and quantity. Moreover, AM can greatly reduce transportation costs and associated emissions and potential waste stream contamination, thus transforming the current recycling system, where currently recycling (particularly of plastic) is not economical in the centralized context (Santander, et al., 2020). “In that matter, the recycling strategy can be linked to the strategy of ‘reducing impact in raw material and sourcing’, where four publications present examples of how local waste, including bio-based materials, can be utilized in AM. (Kravchenko et al., 2020).

An eco-design concept is a key approach in reducing the environmental impact of products by focusing on minimizing negative environmental impacts during the design, development, and engineering phases, as seen in the previous “Challenges for promoting Circular Economy in the Early Design Stage” Subchapter. The initial product design has a significant impact on the environmental burden during the later stages of the product's life cycle (manufacturing, use, and end of use) and so, implementing eco-design principles, such as using materials with lower environmental impact and reducing resource use, can improve the sustainable performance of AM processes.

The three dimensions of eco-design for AM are AM technology, product design, and ecological sustainability, which focus on the capabilities of different AM processes, material design, and reducing environmental impacts and resource efficiency (Hegab et al., 2023). Based on the three pillars of sustainability, the benefits of spreading the application of AM technology can lead to improved resource efficiency. Although manufacturing methods and products may be adapted for AM, advantages can be obtained during both the production and consumption phases to product life extension, achieved by technical solutions such as repair, remanufacturing, and refurbishment, as well as more sustainable socioeconomic structures such as improved person-product affinities and deeper relationships between producers and consumers. Moreover, this can lead to reconfigurable value chains: these chains can be accomplished via shorter and more simple supply chains, localized production, innovative distribution tactics, and new alliances (Zhang et al., 2022).

An emergent field is the potential contribution of AM to these circular strategies (Sauerwein et al., 2019). In fact, AM technologies are widely used in concept development (Laverne et al., 2019) and could represent an important instrument for enhancing CE during the EDS of product development. Moreover, what emerges from the literature review is the "lack of environmental and lifecycle considerations in the curriculum for the Early Design Stages" (Markou et al., 2017). Designers are facing a challenge in finding appropriate approaches for incorporating AM into the early design phases (Valjak and Bojčetić, 2019). To assist designers in reducing the environmental impact of AM, two methods have been proposed. The first method is involving experts in AM during the EDS. The second method is providing designers with tools specifically designed for their work. These methods can also be applied to other areas beyond AM (Laverne et al., 2019).

Design by Additive Manufacturing and Opportunities Object

Design by Additive Manufacturing (DbAM) is a rapidly growing field that has attracted significant attention in recent years due to its potential to revolutionize the manufacturing industry. The ability of AM to create complex geometries and customized products has made it an attractive option for manufacturers looking to produce innovative and high-quality products. DbAM refers to the process of designing products specifically for AM, considering the unique capabilities and limitations of the technology. With the increasing emphasis on CE principles, DbAM has become a critical area of research and innovation

Within the context of DbAM, a useful supporting tool for inspiring the application of AM in product design is described by Lang et al., in 2019.

The authors defined fourteen opportunities of the potential of AM (topology optimization, material choices, multi-materials, monoblock...) and represented them in fourteen inspirational objects, each associated with one opportunity described later. They proved that such methodology can help foster innovative ideas through associations between product sector-specific knowledge and the potential of AM (Lang et al., 2021). These fourteen objects have been used in this work and implemented in the tool proposed for empowering CE, as described in the next Chapter.

The industry has quickly realized the importance of bringing creativity into product design. The industrial context requires robust and efficient methods and tools to access untapped sources of ideas. Furthermore, AM offers a large potential for creativity in product design (Lang et al., 2019). Design thinking could be very useful for business model innovation as well. In fact, the design and implementation of new business models involve multiple considerations such as the attributes of the business model as a tool, the interrelationship between its components, the relationship with product market strategy and organizational design, the design elements and themes that contribute to value creation, the conflicts with existing business models, sustainability, and the role of managers as designers and executives (You, 2022). In this context, utilizing tangible tools is very important and could represent the keystone of an innovative industry.

The literature highlights the effectiveness of methodologies based on tangible tools, such as cards or objects, to generate creativity. The difficulty with such tools is to be inspirational as well as formative. Therefore, the article by Lang, in 2021, presents a method to help designers capture the design potential of AM to design creative solutions at the EDS, named the Augmented Design with AM Methodology (ADAM2). As said, in the ideation phase, crucial design choices are made. It is essential to incorporate AM specifics during this early stage for two key reasons:

1. to foster creativity
2. to bring in AM knowledge as early as possible to overcome conventional manufacturing limitations.

In Lang's work, the potential of AM has been defined by 14 characteristics divided in 4 macro-categories, referred to as the "opportunities" of AM. These opportunities are based on opportunistic Design for Additive Manufacturing (DfAM) methods, which aim to help designers navigate the technical complexities of AM and are below listed (Lang et al., 2021).

- <u>Opportunities of shape complexity</u>:

1. Freeform shapes: AM enables the creation of almost any shape by building up material layer by layer, which offers greater design freedom.
2. Objects from 3D scans: AM and 3D scanning can be combined to create custom designs based on existing geometries.

    1. Opportunities of hierarchical complexity:

3. Microstructure variation: AM allows for variation in the microscopic structure of a product, which can impact its mechanical, physical, and technical properties.
4. Texture: The surface roughness and texture of a product can be adjusted, influencing its surface and structural mechanical properties.

    2. Opportunities of functional complexity:

5. Monoblock: AM can integrate multiple parts into one piece, eliminating the need for assembly.

6. Topology optimization: AM allows for material optimization to reduce product weight through topological optimization using organic geometries.
7. Unassembled mechanisms: AM can produce kinematic joints, allowing for the creation of mechanical connections during manufacturing.
8. Segmentation: AM can manufacture parts as separate components, enabling the creation of kits.
9. Embedded components: AM can encapsulate elements within a product, allowing for the integration of electronic components or increased mechanical properties.
10. Internal channels: AM can create internal channels to improve product performance and reduce the risk of leaks.
11. Infilling: AM can adjust internal filling patterns, impacting the object's mechanical, physical, and technical properties and costs.
12. Auxetics structure: AM allows for modification of Poisson's module to create structures that transmit stress by deformation or absorb stress through compression.

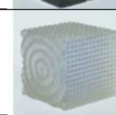
3. Opportunities of material complexity:

13. Material choices: AM offers a wide range of material options, including plastic, metal, ceramic, sand, and composites, enabling adaptation to the needs of different applications, particularly in medicine.
14. Multi-materials: some AM machines allow the design of multi-material parts. It is thus possible to manufacture composite materials with several plastics to mix different metals and even to combine materials of different natures.

In the 2021, in Lang et al. work entitled “Augmented Design with Additive Manufacturing Methodology: Tangible Object-Based Method to Enhance Creativity in Design for Additive Manufacturing”, it has been chosen to present one opportunity per object to facilitate the understanding of the different opportunities, especially for novice designers in AM.

Table 7 The “Opportunity Objects” by (Lang et al., 2021). For each AM opportunity (left column), an object representation (right column) is given.

AM Opportunity	**Object representation**
Segmentation	
Embedded components	
Internal Channels	
Infilling	

Auxetics structure	
Material choices	
Multi-materials	
Freeform shapes	
Objects from 3D scans	
Microstructure variation	
Texture	
Monoblock	
Topology optimization	
Non assembled mechanisms	

The opportunity objects are cube-shaped objects with a size of 3 cm on each side used to represent opportunities in the design process shown in Table 7. In the next lines, the study procedure is described.

The cubes were made using three different manufacturing processes: selective laser melting, material jetting polyjet, and fused deposition modeling. The objects have been evaluated by three groups of participants - 18 students, 6 professors, and 5 industrialists - to validate their design and ensure that each of them represented the opportunities effectively. The evaluation consisted of verbalizing the objects, and participants wrote down all the words that came to mind. Two different scores could be assigned: 0 and 1. A score of 1 was given when the name of the opportunity or a synonym was given, and a score of 0 was given otherwise. The results showed that eight objects were validated, and four objects (texture, monoblock, segmentation, multi-materials) were improved, with two of them (topology optimization, material choices) having metal incorporated into their design. The participants also suggested that a short presentation of the objects could improve their understanding. The evaluation results are, therefore, positive.

These fourteen objects have been used in this work and have been implemented in the tool proposed for empowering CE, as better described in the next Chapters.

Synthesis

CE is a modern concept that has gained significant attention in recent years, with numerous definitions and ways of conceptualizing the CE identified. CE aims to change the way we use and manage resources and materials, from a linear model to a circular one. In this State of the Art, it has been possible to better investigate the link between AM, CE, and EDS, highlighting the lack and the possible areas for development.

The integration of AM and CE, in fact, can bring many benefits, such as personalizing products, creating new value propositions, reducing costs, improving control over material quality and quantity, and reducing transportation costs and emissions. AM technologies can also enhance CE during the EDS of product development. However, there is a lack of environmental and lifecycle considerations in the curriculum for the EDS, and designers face challenges in incorporating AM into their design process. To overcome this, experts in AM can be involved during the EDS or designers can be provided with tools specifically designed for their work.

The concept of Design for a CE is a crucial area of focus for sustainable product design and development. The objective of this approach is to extend the product life and recover products and materials through a hierarchy of strategies, promoting high-value and high-quality material cycles. Companies need to prioritize sustainability to stay competitive in the market, and eco-design is one approach they can take to reduce the environmental impact of their products throughout their entire lifecycle. Designing products with CE in mind requires considering the impact of materials and resources used throughout the product's life cycle and making decisions in the EDS to avoid costly changes later in the process.

An important tool, the Augmented Design with AM Methodology (ADAM2), for empowering the application of Design by Additive Manufacturing (DbAM) in product design has been analyzed in this State of the Art. The tool is based on the work of Lang et al. (2019), which defines 14 opportunities of the potential of AM in product design and represents them in 14 inspirational objects. The tool helps designers capture the design potential of AM to design creative solutions at the EDS by incorporating AM knowledge as early as possible during the ideation phase. The 14 opportunities of AM include shape complexity, hierarchical complexity, functional complexity, and material complexity, each with its own specific characteristics, such as freeform shapes, monoblock, material choices, and multi-materials. The literature supports the use of tangible tools, such as the ADAM2, to generate creativity and support the design and implementation of new business models.

To conclude, CE's current State of the Art showcases its potential as a revolutionary alternative to the traditional linear economy model. Unlike the linear model which mainly

focuses on end-of-life waste management, CE takes into account all inputs and outputs of the production process with a strong emphasis on resource management. In the literature, there is a lack of understanding and education on circular design among customers, and tools and resources should be made available to educate stakeholders and demonstrate the feasibility of the circular design.
In fact, despite its immense potential, there are several challenges that impede the integration of CE principles in the EDS of product development. One of the major challenges is the lack of tools and limited research in the field. This makes it difficult for businesses to adopt CE principles in their product development process. Furthermore, the existing methodology within the framework of Eco-Design and AM does not provide adequate support for CE principles. This highlights the need for further research to examine the intersection of CE and AM and to overcome the limitations in the field. The development of new tools is crucial for improving CE in the design stage. Such tools should not only help unlock the full potential of CE in product development but also play a significant role in promoting sustainable production practices.

Overall, this thesis research is focused on understanding the integration of CE principles in the EDS of product development because of the lack of tools in this research area and it is crucial for ensuring a sustainable future and mitigating the negative impacts of production on the environment.

4

CIRCULAR ECONOMY DECK TOOL

Tools for creativity

Having understood the effectiveness of methodologies based on tangible tools, such as cards or objects, to generate creativity during the EDS of product development. The difficulty with such tools is to be inspirational as well as formative (Lang et al., 2021).

The tools in the field can be categorized into six different categories (Peters et al., 2021).

1. *Methods*: many tools are essentially collections of design methods or creativity strategies, and can be seen as a deck of method cards.
2. *Prompts*: a number of tools include provocative questions, triggers, or abstract visuals to encourage divergent thinking.
3. *Components*: tools in this category include placeholders, such as cards, tiles, or pawns, that represent different components of a system or problem, enabling them to be visualized, rearranged, and kept in focus during collaboration.
4. *Concepts*: tools in this category present expert knowledge in a manageable form, such as short descriptions of psychological theory on individual cards, making it easier to learn, share, and represent.
5. *Stories*: a few tools utilize narratives as part of their approach, for example, a story to illustrate the use of a strategy or as a prompt.
6. *Embodiment*: one tool, the Cambridge Inclusive Design Toolkit, incorporates analog simulation of embodied experience through the use of glasses and gloves to allow designers to directly experience reduced visual and manual ability.

The combination of physical design, circular business models, and value chain interactions is crucial in ensuring circularity. There is ongoing research in developing appropriate knowledge and methods to support design for CE in both micro and meso scales. Design strategies such as *Design for Disassembly*, *Design for Repair and Maintenance*, and *Product-Service Systems* are found to be enablers for circular buildings and products (Dokter et al., 2022).

The move from a linear to a CE will likely impact the roles of designers in both the built environment and consumer product industries. Product designers, as noted by Rios et al. (2017), will need to deepen their material knowledge, gain proficiency in service design, and have a stronger understanding of social behavior.
Sumter et al. (2020, 2021) identified specific skills and competencies for industrial designers that are relevant to the CE, such as the ability to anticipate future product cycles, evaluate environmental impacts, collaborate more effectively with stakeholders, and tell compelling stories about the value of the CE to both internal and external parties. In the architectural context, Galle et al. (2015) emphasized the need for designers to shift from short-term involvement to longer-term engagement to promote lifecycle thinking and the careful management of buildings.

Kozminska (2019) argued that the circular design process differs significantly from traditional design methods, as demonstrated through a series of architectural case studies. As such, the design process must involve interdisciplinary collaboration and must consider the lifecycle of materials in order to establish methods for future maintenance, disassembly, and material reuse. Finally, Kanters (2020) discussed how architects can play a crucial role in the transition to a CE by connecting various actors, such as clients, contractors, and engineers, but they will need to cultivate leadership skills and work with greater flexibility in the design processes, while also gaining a deeper understanding of materials and construction.
Inizio modulo
Fine modulo

A high number of customers are hesitant to embrace circular design due to a lack of understanding and education on its value and feasibility. To overcome this, tools and resources should be made available to educate stakeholders and demonstrate the practical applications of circular design. Despite being seen as a theoretical concept, many inspiring examples of circular design can help broaden perspectives and show its feasibility. The complexity of circular design can be a challenge, as it requires a deep understanding of various parameters and lifecycle considerations. To mitigate this, the design process can be made more manageable by contextualizing it and focusing on specific challenges while still maintaining a holistic perspective. This can be achieved by providing information on relevant business models, material alternatives, and lifecycle considerations.
Another issue is the lack of a unified definition and understanding of circular design, which can lead to a lack of collaboration between local stakeholders and experts in the design process. To address this, tools should be developed to align definitions, facilitate collaboration, and support stakeholders throughout the design process and product lifecycle (Dokter et al., 2020).

Considering the necessity to use such tools during the product design phase, a literature review has been conducted to investigate which tool is considered the most useful for empowering creativity in the designers and to let them focus on circularity concepts. As a result, it has been highlighted that card-based tools have all the characteristics to help designers and other stakeholders during the ideation phase of an innovative product.

In fact, the card-based format was selected for its benefits in ideation processes in design practice, as it offers a middle ground between unstructured tools, such as post-it notes, and structured information like instruction manuals. Literature suggests that this format provides summarized, semi-structured information, making it a useful tool for designers. "Users describe cards as valuable for sparking creativity, externalizing tacit concepts, constructing and organizing ideas, and working both playfully and collaboratively" (Logler, Yoo, 2018).

As said, the literature shows CE tools with cards have been considered the most useful and two examples of cards used for empowering CE have been valuable to orient the work of this thesis project.

The first, the *Circular from Circularity* (CfC) tool, shown in Figure 11, comprises a variety of cards, each of which provides a circular design option for a specific sub-parameter of circular design. These design parameters refer to the choices that designers must make in a circular design, including the application of circular design strategies, selection of materials, and product cycles (Dokter et al., 2020). The tool is created with three colors of cards, distinguishing the technical model (the physical design of example a product or building), the industrial model (supply chain management), and the business model (marketing and finance). The tool can be used in different contexts and phases of the design process, from ideation to conceptualization. The study aimed to gather insights into the design for a CE and to explore how design tools, specifically the CfC, can support the design process. It was conducted in several steps: reviewing existing circular design methods, developing the card-based circular design tool, as in Figure 11, conducting an interactive survey with design experts, and organizing a design workshop using the CfC.

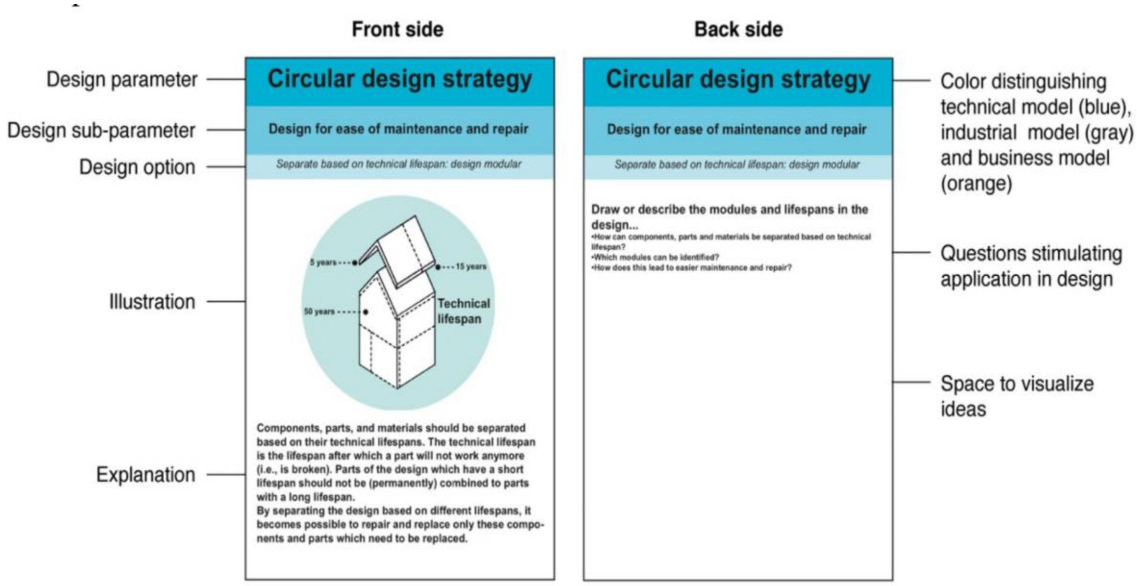


Figure 11 An example of a card for the design parameter 'Circular design strategy' and sub-parameter 'Design for ease of maintenance and repair' by (Dokter et al., 2020).

The second research paper focused on a Card Deck tool is represented in Figure 12. The Circularity Deck, presented by Konietzko, is a tool that allows users to assess, brainstorm, and enhance the circularity potential of their innovation systems. It incorporates product, business model, and ecosystem innovation concepts that can restrict, reduce, complete, renew, and educate the flow of materials and energy within a specific environment, and examine the key players required to achieve this. As shown in Figure 12, the deck features example cards with different colors signifying the circular strategy: orange signifies '*restrict*', red '*reduce*', blue '*complete*' and green '*renew*'. The front of each card displays a principle and identifies it as a product, business model, or ecosystem principle (bottom left of the front card). The back of each card includes a brief explanation of the principle and a corresponding example (Konietzko et al., 2020).

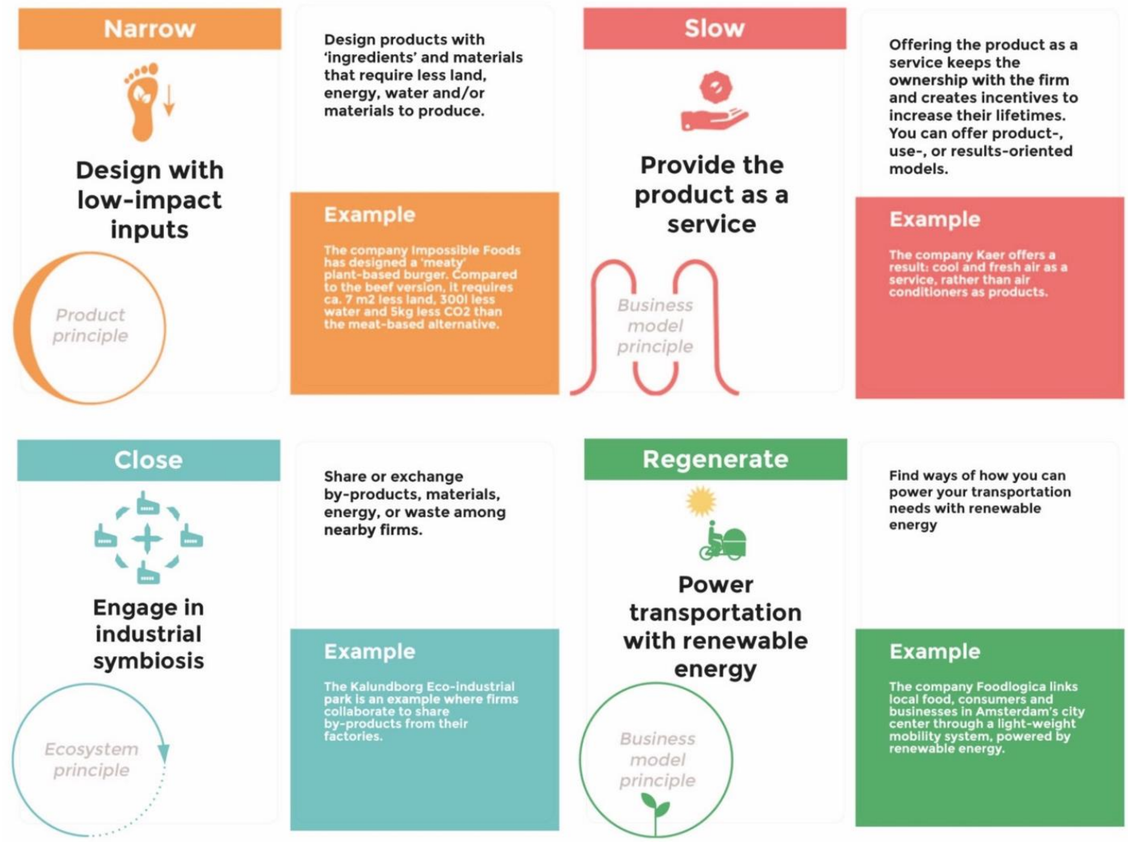


Figure 12 Example cards from the Circularity Deck by (Konietzko et al., 2020).

The Circularity Deck, proposed by Konietzko, in 2020, can be used to analyze and develop the circularity potential of innovation ecosystems in each context and bridge the theory-practice gap in organizational research. As a practical contribution, the Circularity Deck provides guidance for future tool development, including the importance of clear and concise descriptions and examples, the potential benefits of an exercise without this type of tool, and the usefulness of an expert facilitator.

It is important to acknowledge the limitations of this study, including that the review of the Circularity Deck is not complete. In fact, the tool has been tested in limited contexts in developed economies, and the tool does not incorporate social and institutional dimensions of the circular economy. Future research may include a set of social and institutional principles to complement the principles proposed in this study.

The card tool will be presented in Chapter 3 and will be used in this thesis project as a tool for empowering creativity during the EDS of product development and for empowering the level of circularity as well.

The research design is a plan that outlines the procedures for collecting, analyzing, interpreting, and reporting data in a research study. It aims to connect conceptual research problems with feasible empirical research by specifying the necessary data, the collection and analysis methods, and how they will address the research question presented in Chapter 1 (Gray, 2009).

The intention of this research design approach is to answer the three questions presented in Chapter 1. As the concept of CE currently interpreted has already been analyzed in the State of the Art, now, designers need further support for implementing CE concepts in product development and need a tool for developing CE as much as possible in the EDS.

The tool below has been ideated to answer this part of question 1 and to answer question 2 as well. Question 3 will be answered thanks to some questionnaires that the participants of the Case Study have filled in.

In the previous literature review Chapter, it was highlighted that integrating CE principles into the EDS is essential for adopting AM as a sustainable production method and that there is a need to better evaluate the link between AM and CE.

First, this research wants to find a tool that can help designers and other stakeholders in paying attention, in general, to sustainability, and more in particular to CE concepts. As highlighted in the previous "Tools for creativity", it has been fundamental to understand which tools are nowadays used for creativity to choose the correct one for this research. Cards have been chosen as an important tool for empowering creativity during the EDS.
Cards are often used in ideation and brainstorming activities to generate, organize, and communicate ideas among team members. Cards can also be used to facilitate the design process by providing a visual and tangible representation of ideas and can be a powerful tool for empowering individuals and communities to act on sustainability issues. Therefore, as cards have proven to be a versatile and effective tool for empowering creativity and fostering collaboration during the EDS of product development, in this work they have been chosen for contributing to the development of innovative and sustainable solutions for designers.

As the necessity to switch from a LE to a CE is increasing day by day and as the evidence of a lack of tools for helping designers in the EDS of product development to pay attention to CE aspects, the research design approach in this chapter aims to introduce a new tool that incorporates a card deck and the fourteen AM opportunities objects, first presented, to assist designers in integrating CE principles.

To conclude, cards have been chosen as the tool proposed because of their importance in empowering creativity during the EDS. It has been developed to maximize the opportunities for CE during the EDS and its effectiveness will be evaluated through an experiment. In the following sections, the tool will be introduced in detail and the experiment protocol will be explained, including the evaluation methods used to assess the tool's effectiveness. The results of this experiment will contribute to the existing body of knowledge on the integration of CE principles and AM in the design phase and will be shown in Chapter 4.

Circular Economy Card Deck

This study proposes a Card Deck tool, named "Circular Economy Deck", as cards are valuable for "sparking creativity, externalizing tacit concepts, constructing and organizing ideas, and working both playfully and collaboratively" (Hureau et al., 2018). Collaborative and open strategies for EDS have been demonstrated as crucial tools for the implementation of successful CE (Panza et al., 2022). The tool can help designers to analyze, ideate, and develop the circularity potential in their projects during the EDS of production. The tool is based on the previous literature review of circular-oriented innovation principles and strategies to realize it. The principles are organized according to the intended circular strategy outcome that they pursue (*narrow, slow, close, regenerate*), and one of the 10R strategies that each card is representing.

The deck is presented with a Legend Card in Figure 13.

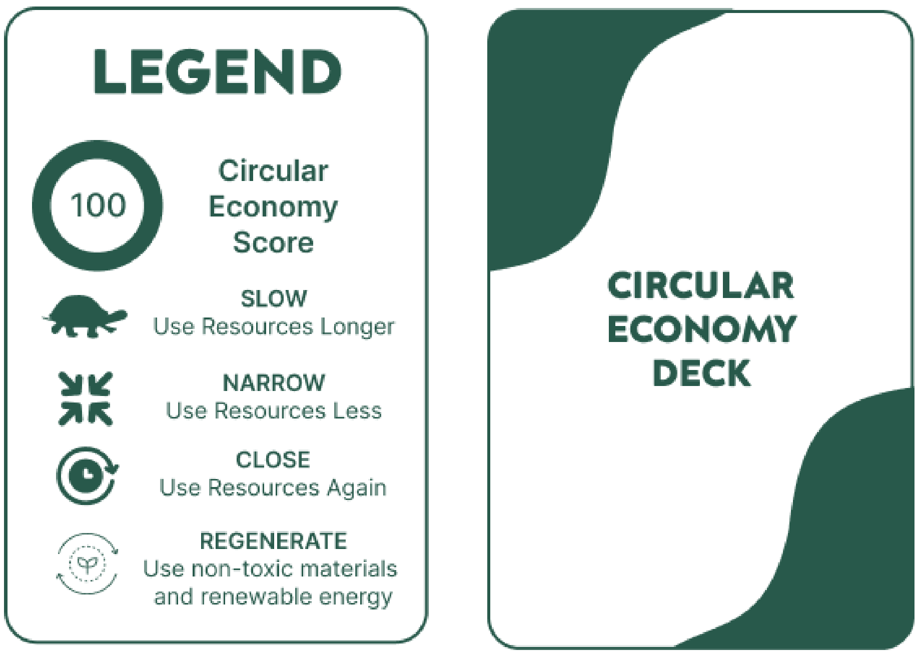


Figure 13 Legend Card of the Circular Economy Deck. The Legend Card shows the symbol utilized for explaining the CE Score and the symbols utilized for the *slow, narrow, close,* and r*egenerate* concepts.

Figure 13 shows the Circular Economy Deck. Each of the ten cards represents a CE strategy on which it is important to be focused. On the back side of the cards, the explanation of the strategy is presented with a user-friendly image, and on the front side a score and the strategic effect between *slow, narrow, close*, and *regenerate* is assigned. The LCA framework, presented before, has been integrated with this card deck by analyzing the effects and the consequences of each strategy on the product life cycle.

To decide the existing link between each strategy and each of the four symbols present or not on the card, an analysis with three experts on the CE framework has been conducted. Specifically, three experts have been asked to rank the most impactful effects between *slow,* *narrow, close*, and *regenerate* for each of the 10 cards. The data have been collected and analyzed and the deck below presented is a result of the average of the answers given by the 3 experts. In each card, each strategy's effects in terms of LCA have been inserted thanks to the symbols presented in Figure 13 and inserted below the title on the front side (green side).

Figure 14 Circular Economy Deck is composed of 10 cards on the front and back (white) sides.

Following, each card, presented in Figure 14, is described more in detail.

1. **Refuse Card**: the definition of the card is to make the product function redundant or offer the same function in a radically different product. The idea behind this card is to think out of the box, not assume any historical baseline, and anticipate consumers' trends as the collaborative corporate ecosystem does. This card is powerful in terms of *slowing* and *narrowing*.
   An example given of this card applied to a business model is the company ByHours. This startup is an online platform that lets customers book stays for 3, 6, or 12 hours in more than 3,000 hotels worldwide, with a pay-per-use system allowing them to choose check-in and check-out times and pay only for the hours they use. This Barcelona-based company is a leader in the industry and has introduced a flexible hotel booking model, with the aim of empowering customers to tailor their hotel stays to their individual needs. For sure, ByHours founder Guillermo Gaspart has applied the Refuse concept.

2. **Rethink Card**: the definition is to take products to use more intensively and efficiently. This card is powerful for *slowing* and *narrowing*.
   An example that could be provided is through sharing products or by putting multi-functional products on the market such as shoes you dot own by Adidas. The famous

brand has created sneakers that you cannot keep but can share with thousands, representing the company's commitment to taking full responsibility for the entire lifespan of its products. This project has a specific focus on reducing plastic waste by utilizing a circular manufacturing model. By doing so, we can repurpose the raw materials repeatedly, rather than creating more waste. The unique aspect of this model is that the materials can be repurposed into another pair of high-performance running shoes, Adidas is rethinking in a new way the usage of the products and materials involved in the production process.

3. **Reduce Card**: the definition is to increase the manufacturing efficiency of the product or consume fewer natural resources and materials. The idea to make the same (ideally more) with less is the backbone of the productivity mindset behind this card. This card is powerful in terms of *narrowing*.
   An example of the reduced card and strategy applied is related to the automation of production processes or to the idea of using lower external inputs such as energy or more efficient raw materials consumption. Another example, in the AM context, is given by all the products that are designed without molds and that require less material.

4. **Reuse Card**: the definition is to use again, by another consumer, the discarded product which is still in good condition and fulfills its original function. This card is powerful in terms of *slowing, narrowing,* and *closing* the resources loop.
   An example that can easily explain the concept behind this card is related to the "corporate Wallapop" idea. Wallapop is a company that operates a marketplace mobile app for trading secondhand goods. Now, the idea is to expand it at a corporate level and so creating a digital platform where you could find second-hand equipment in good condition sold by a competitor for instance. Another example, in the AM context, is reusing a bit of a scrap of AM in the next project.

5. **Repair Card**: the definition is to repair and maintain a defective product so it can be used for its original function. This card is powerful in terms of *slowing, narrowing*, and *closing* the resources loop.
   An example, in the AM context, is the extensive use of 3D printing to repair old things with no spare parts available.

6. **Refurbish Card**: the definition is to renovate an old product to bring it up to date. This process is typically less intensive than remanufacturing, which results in a final product comparable to a brand-new product. This card is powerful for *slowing* and *narrowing*.
   An example of this strategy applied consists in buying refurbished tech devices such as iPhones or laptops.

7. **Remanufacture Card**: the definition is to use parts of discarded products in a new product with the same function. This card is powerful in terms of *slowing, narrowing*, and *closing* the resources loop.
   An example is the Circular Computing Company which has invested millions over the years to ensure that its remanufactured laptops can aid everyone in neutralizing

carbon in their IT supply chains. Remanufacturing can be distinguished from refurbishing or reconditioning as the like-new second-hand product matches the consumer's expectation of appearance and performance as if the product were brand new, as the website of Circular Computing declares.

8. **Repurpose Card**: the definition is to use discarded products or their part in a new product with a different function. This card is powerful in terms of *slowing*, *narrowing,* and *closing* the resources loop.
   An example of this strategy applied is given by the design collective Andra Formen which makes furniture from discarded electric scooters.

9. **Recycle Card**: the definition is the process material to obtain the same or lower quality. This card is powerful in terms of *narrowing, closing* the resources loop and *regenerating*.
   An example is Allegories' Case Study, a women-owned company producing high-quality, cruelty-free, and PVC-free accessories out of discarded fruits.

10. **Recovery Card**: the definition is the incineration of material with energy recovery. In the end, recovering is the process of giving value to a material believed to be waste. Recovering means transforming waste into resources. This card is powerful in terms of *closing* the resources loop and *regenerating*.
    The best example of recovery is composting. It transforms our fruit and vegetable wastes into rich soil conditioners, commonly known as compost.

Tool evaluation methodology

After having presented in the previous Subchapter the card tool created, we delve into the practical implementation of the theoretical concepts and tools discussed in earlier Sections. In this Subchapter, we will see how the experiment for evaluating the tool has been thought.

The methodology has been created to evaluate the effects of using the Circular Economy Deck during the EDS of a product and to further explore the relationship between CE and AM. To achieve these objectives, the methodology was divided into five distinct phases, each designed to incorporate specific aspects of creativity, CE information, and AM knowledge.

Table 8 Phases of the experiment and time scheduled for each phase.

<table>
<tr><th colspan="2"></th><th>Phase 1: Introduction to Additive Manufacturing processes</th><th>Phase 2: Introduction to Circular Economy concepts</th><th>Phase 3: Presentation of the Card Deck for Circularity and of the AM Opportunities Objects</th><th>Phase 4: Creativity session “The foldable helmet of the future”</th><th>Phase 5: Questionnaires</th></tr>
<tr><td></td><td>Group using Card Deck</td><td rowspan="2">5’</td><td rowspan="2">15’</td><td rowspan="2">15’</td><td>125’</td><td>10’</td></tr>
<tr><td></td><td>Group without Card Deck</td><td>125’</td><td>10’</td></tr>
</table>

Table 8 describes the approach used for evaluating the Cards-based tool, presenting the time necessary for each phase and when the participants will be split into different groups.

5 phases composed this approach:

- 1st phase: participants are introduced to AM Processes through a presentation with PowerPoint. This phase lasts 5 minutes.
- 2nd phase: participants are introduced to CE concepts through a presentation with PowerPoint. This phase lasts 15 minutes.
- 3rd phase: present and explain each card of the Circular Economy Deck to the participants. Then, participants are introduced to Lang’s AM opportunities objects, described previously. This phase lasts 15 minutes.
- 4th phase: this phase is dedicated to the Creativity Session. The participants are separated into 2 groups. Participants in the 1st group use the Circular Economy Deck to generate their idea sheet and those from the 2nd group do not use it. Both groups use the 14 AM opportunities cubes. An expert in charge of the Creativity Session presents the brief. This phase lasts 125 minutes.
- 5th phase: after having realized the Creativity Session using brainstorming, purge phase, and inversion phase to offer a maximum of Idea Sheets (IS), students are asked to fill in different questionnaires. This phase lasts 10 minutes.

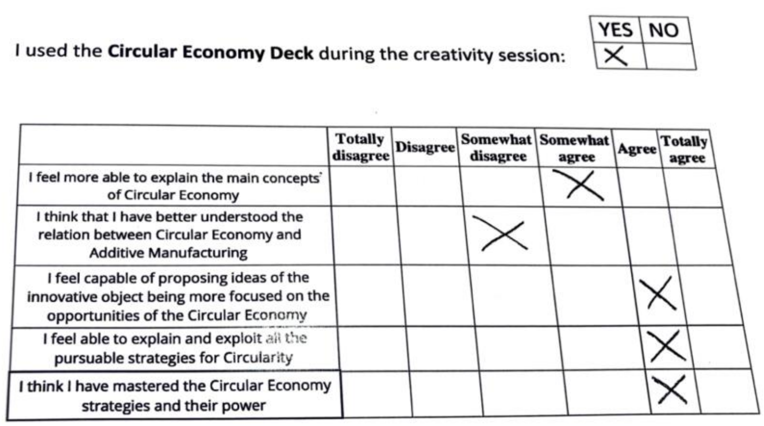
During the 1st and 2nd phases, students were given a short lesson on AM and CE to briefly explain these concepts to prepare them for an in-depth analysis. The intention of this lesson was also to make the participants focused on what are the key and main themes of the research work that was done to direct their actions during the next stages on these topics.
During the 4th phase, participant-generated IS should contain a graphic representation of the designed and proposed product with a written list of the pros and cons of this product. If the

product design is difficult to understand from the image alone, participants are asked to write down some additional useful information to make the idea easier to understand. During the 5th phase, different questionnaires have been created to collect different data. These different questionnaires were proposed to all participants to assess their feelings about this approach. Five questions, presented in Table 9, are created to understand participants' interests, their perceived acquisition of CE knowledge and the application of these concepts for developing the idea, and their perceived acquisition of CE knowledge related to AM processes. In addition, those who used the Card Deck must declare which cards have been used in the development of their idea.

Table 9 shows the list of questions of the 1st questionnaire and Figure 15 gives an example of how it should be filled in.

Table 9 List of questions asked to the participants.

List of questions
I feel more able to explain the main concepts of CE
I think that I have better understood the relation between CE and AM
I feel capable of proposing ideas of the innovative object being more focused on the opportunities of the CE
I feel able to explain and exploit all the pursuable strategies for Circularity I think I have mastered the CE strategies and their power



I used the **Circular Economy Deck** during the creativity session:

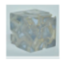
YES	NO
X	

	Totally disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Totally agree
I feel more able to explain the main concepts of Circular Economy				X		
I think that I have better understood the relation between Circular Economy and Additive Manufacturing			X			
I feel capable of proposing ideas of the innovative object being more focused on the opportunities of the Circular Economy					X	
I feel able to explain and exploit all the pursuable strategies for Circularity					X	
I think I have mastered the Circular Economy strategies and their power					X	

Figure 15 The form filled in by a participant.

Furthermore, participants are asked to complete the matrix shown in Table 10 for evaluating the relationship between each of the 14 AM cubes and the CE strategies presented in the cards. We asked the students to rank the top 3 CE strategies more powerful for each cube and so more related to each opportunity the AM cubes want to refer to.

Table 10 Matrix to fill in to rank the relationship between CE strategies and AM opportunities. Each cube is different from the others and represents one AM opportunity. This matrix has been used to evaluate how much each opportunity is impactful on CE strategies.

AM CUBES / CE STRATEGIES	 1	 2	 3	 4	 5	 6	 7	 8	 9	 10	 11	 12	 13	 14
REFUSE														
RETHINK														
REDUCE														
REUSE														
REPAIR														
REFURBISH														
REMANUFACTURE														
REPURPOSE														
RECYCLE														
RECOVERY														

1. Segmentation
2. Embedded components
3. Internal channels
4. Infilling
5. Auxetics structure
6. Material choices
7. Multi-materials
8. Freeform shapes
9. An object from 3D scans
10. Microstructure variation
11. Texture
12. Monoblock
13. Topology optimization
14. Non-assembled mechanisms

5

TOOL EXPLOITATION AND EVALUATION

Tool exploitation

After having presented the methodology and the different phases of which it is composed, in this Chapter it will be defined how the experiment has been conducted and in which way the methodology has been applied. Moreover, in this Chapter, we will understand how to exploit the tool and evaluate it.

The experiment has been conducted in the LCPI at Arts et Métiers - Sciences et Technologies ParisTech on Friday the 2nd of December 2022. The participants are twelve master's students of Product Design and Innovation.

The five phases are performed exactly as described earlier.

During the 1st phase, participants are introduced to AM concepts through a presentation with PowerPoint. The introduction to the topic has been held by Professor Frédéric Segonds, Full Professor at Arts et Métiers Institute of Technology in Paris, where he is renowned for his expertise in collaborative design, PLM, and Design and Creativity with AM. His research has a particular focus on the EDS and is conducted at the CPI Laboratory. To present the topic of AM, the expansion that the AM market has been experiencing in recent years was highlighted. In fact, a growth of +23% per year is estimated for the next 5 years. Then, the potential of AM and the complexities of AM were exposed. These AM-related complexities explain mostly the geometry, hierarchy, choice of materials, and functionality of final products (Gibson, 2015).

During the 2nd phase, participants are introduced to CE concepts through a presentation with PowerPoint. First, the definition of CE was given, and CE was compared with the concept of sustainability. Next, a list of the 10R key strategies for moving from an LE to a CE was provided with an overview of how LCA can be useful for the purpose of evaluating actions for CE as well. Some slides of the PowerPoint Presentation used during these two phases are presented in Appendix A.

In the 3rd phase, each card of the Circular Economy Deck to the students has been explained. Participants are also introduced to the AM opportunities objects. The fact that the participants had already used the AM opportunities objects allowed them to be totally focused on the Card Deck and on how to use it. This is not important information for performing the experiment correctly, but it is noteworthy information. All the information presented in the Circularity Economy Deck tool subchapter was given to the participants.

After the 3rd phase, the twelve participants were separated into two groups both composed of six people. The groups have been divided into two different rooms and they spent the same time for each of the parts of the Creativity Session. It's at this moment that the 4th phase started. During the 4th phase, the Creativity Session has been conducted.

Figure 16 gives some more insights into the Creativity Session held during the 4th phase. The product on which the participants have worked is: "*The foldable helmet of the future*". During the purge step, they had to focus on the foldable systems they already know, then, during the inversion, on the worst foldable helmet they could imagine designing. After these 45 minutes, they had to generate IS, as pictured in Figure 17, and then, the last 20 minutes have been dedicated in the evaluation of these IS.

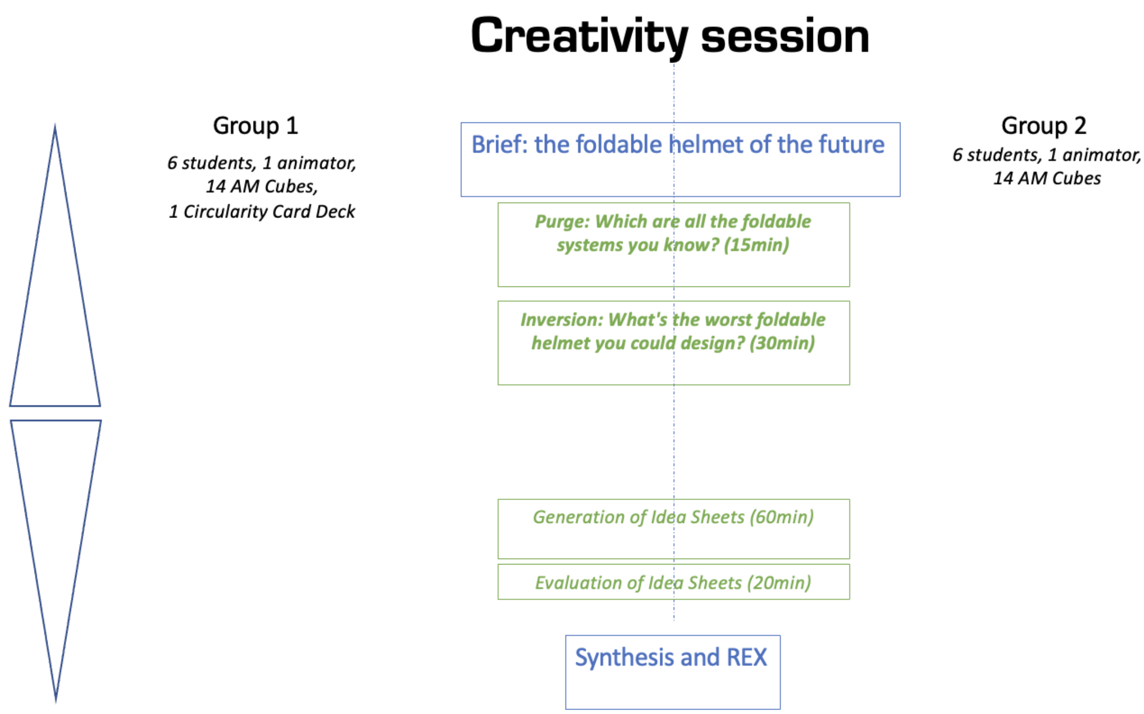


Figure 16 Structure of how the Creativity Session in the 4th phase must be conducted. The creativity session is divided into different stages. After the topic is presented, during the purge phase participants must think about the foldable helmet already present in the market. Then, during the inversion phase, they had to design their version of the worst foldable helmet. Later, the Idea Sheets were generated and evaluated.

Figure 17 A picture of the participants during the Creativity Session. The participants are filling in their Idea Sheets, after having used CE cards and the opportunity objects. Other pictures are presented in Appendix B.

Results

During the 5th phase, different questionnaires were proposed to all participants to assess their feelings about this approach. Five questions were asked to understand participants' interest, their perceived acquisition of CE knowledge and the application of these concepts for developing the idea, and their perceived acquisition of CE knowledge related to AM processes. In addition, students who used the Card Deck must declare which cards have been used in the development of their idea.

In total, eight Idea Sheets (IS) were generated (Appendix C). The 1st group, which used the Card Deck, realized four IS and the 2nd group realized four IS as well. Figure 18 presents an example of one of them. It is a new concept of a foldable bike helmet as the Creativity Session theme was "*The foldable helmet of the future*". In Figure 18, the innovative helmet is thin and retractable, when it is closed it looks like a headband and it unfolds as painted protecting the head and spine. The materials involved in the production are entirely recycled.

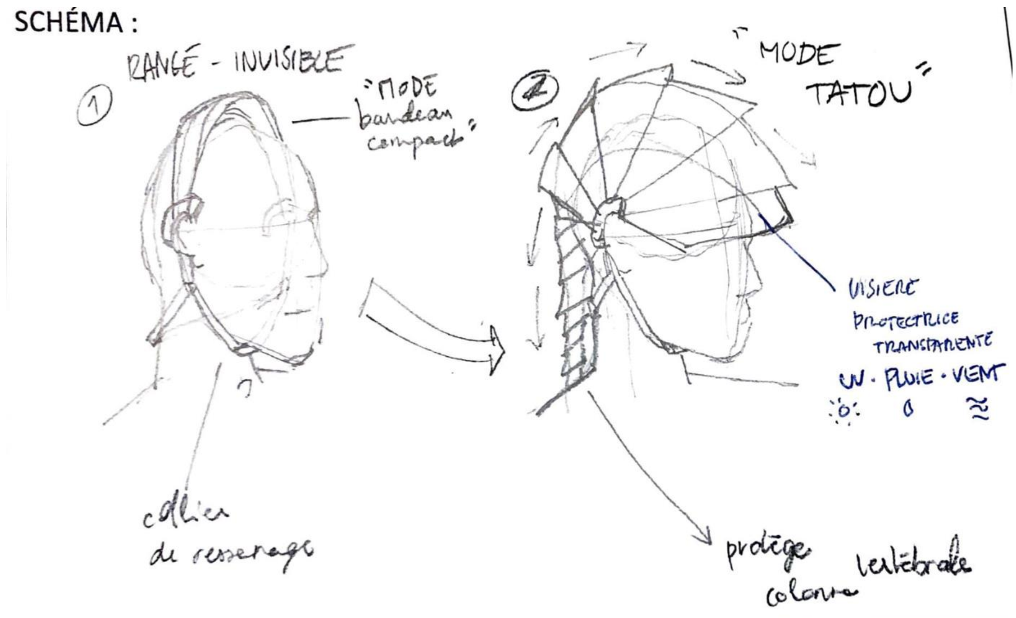


Figure 18 Example of a spontaneous generation of an idea for the ''Foldable helmet of the future''.

Results on circularity level

The students have been asked to declare which cards they used for developing the Idea Sheet and the results, shown in Table 11, reveal that the most used cards are *Reuse*, *Repair*, and *Recycle*. These three cards have been used for each idea generated with the Card Deck. The average of cards used by the students is 4 cards for each Idea Sheet created, this result is a good clue to declare that the tool helps designers in being focused on circularity's aspects during the EDS.

Table 11 Table counting how many times each card has been used by the 6 participants with the Card Deck.

Card	Number of uses
REUSE	5
REPAIR	5
RECYCLE	5
REDUCE	4
REFURBISH	4
REMANUFACTURE	4
RETHINK	3
REPURPOSE	3
RECOVERY	2
REFUSE	1

Results on the feeling of CE performance

Students have been asked to answer the questions presented in Table 9 choosing their answer on a scale of agreement, an example of the questionnaire filled in is given in Appendix D. The answers permitted were Totally Disagree, Disagree, Somewhat Disagree, Somewhat Agree, Agree, and Totally Agree and they have been transposed to a scale from 1 to 6.

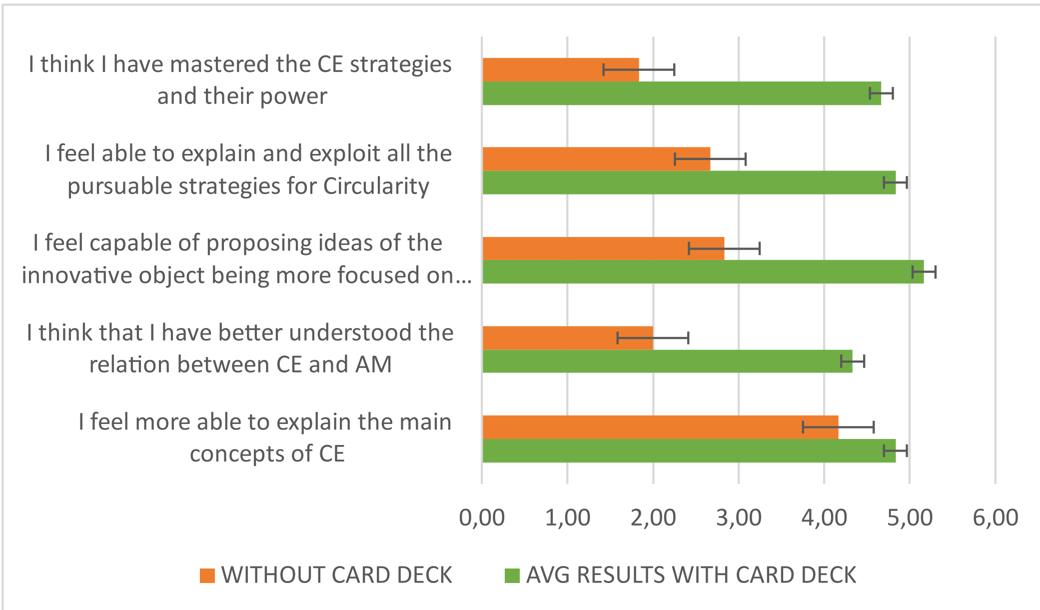


Figure 19 Results of the satisfaction questionnaire (6 students per panel).

The results of this questionnaire indicate a better understanding of the CE strategies among the group of participants who utilized the Circular Economy Deck. This is confirmed by the participants themselves, who reported feeling more able to explain and apply the strategies related to CE. Additionally, those who used the Card Deck stated that they felt more capable of proposing ideas for innovative products, with a greater focus on CE opportunities – which aligns with the intended purpose of the tool. Furthermore, the participants reported that the relationship between CE and AM was clarified and better understood with the tool provided. To further confirm the effectiveness of the research approach, it has been asked to the students if they felt more able to explain the main concepts of CE. The results of this question show that the gap between the two groups is not as significant as for the other questions even if present, suggesting that the 2nd phase of the research was useful and confirming the previous results. Overall, the students' positive feedback and a better understanding of CE strategies using Circular Economy Deck provide valuable insights into the field of PLM.

Results on the link between AM and CE

The results of this table confirm and empower the strong link already studied between AM and CE strategies. The students were asked to rank the top 3 strategies most powerful for each cube and more related to each AM opportunity (Appendix D). Table 12 represents the correlation between each strategy and each cube because of the data collected after counting the times each strategy has been declared in correlation with the others from the data collected in Table 11. The red cells are those characterized by a low level of correlation between the strategies and the AM opportunities, this is also represented by values from 0 (lowest) to 10 (highest) grades of correlation.

The AM opportunities with the highest number of strategies associations are non-assembled mechanisms, material choices, segmentation, and objects from 3D scans. The non-assembled mechanisms represent the possibility, in AM, to make mechanical connections during manufacturing and are very linked with Rethink, Reuse, Recycle, and Repurpose. Thanks to material choices, AM gives the possibility to work with a large choice of materials: plastic, metal, ceramic, sand, composite, etc., this study reveals the strong connection with the Refurbish, Reuse, and Repair strategies. Segmentation, in AM, means the possibility to manufacture the parts of an assembly separately to create a kit. This design in the kit allows the manufacturer to remanufacture only defective parts. The strategy most connected is Remanufacture, followed by Repair and Recycle. By combining 3D scanning techniques and AM, product design is customizable, this opportunity highlights the ability to design based on an existing geometry to improve product properties. Considering the meaning of this opportunity cube, it is not surprising that Rethink and Refuse are the most rated strategies.

In contrast, the AM opportunities that are less related to CE strategies are multi-materials, embedded components, and infilling. Some AM machines allow the design of multi-material parts, manufacturing composite materials with several plastics, mixing different metals, and even combining materials of different natures. This result confirms that mixing different elements in a product design may improve its functionality or performance, but it can also make the product more difficult to recycle or reuse at the end of its life. For instance, a product made of multiple materials may require specialized recycling processes, which can be expensive and energy intensive. For these reasons, this opportunity alone is not impactful in terms of CE, but it should be implemented with others AM opportunities I order to pursue a higher grade of CE. This is related, as for multi-materials opportunities, to embedded components and infilling opportunities as well.

The strategies that resulted in being the most related to AM processes are Rethink, Reduce, Recovery and Reuse. Rethink can be applied, in the AM context, for stimulating new value proposition and for the customization of the products.

Table 12 Table showing the relationship between AM opportunities and CE strategies.

	Non assembled mechanisms	Material Choices	Segmentation	Objects from 3D scans	Texture	Topology optimization	Internal Channels	Microstructure variation	Monoblock	Freeform shapes	Infilling	Auxetics structure	Embedded components	Multi-materials
RETHINK	8	3	4	8	0	5	6	2	1	1	6	3	2	4
REFURBISH	5	10	2	1	7	2	0	0	0	6	2	0	1	3
REPURPOSE	6	2	2	1	6	0	1	1	3	0	3	2	4	2
RECOVERY	3	4	3	0	10	3	0	5	5	1	0	3	5	2
REPAIR	4	5	8	6	0	2	4	0	0	0	0	0	0	1
REDUCE	3	4	0	5	7	8	7	1	2	3	5	7	0	0
REUSE	6	6	6	1	0	0	3	3	3	5	3	1	3	0
RECYCLE	6	3	3	6	2	0	4	5	6	0	1	0	0	0
REFUSE	3	1	3	8	2	4	2	6	3	4	0	4	0	0
REMANUFACTURE	3	2	10	1	0	5	0	2	0	3	0	0	2	0

In addition, an attempt was made to evaluate the IS generated after the creativity session to try to highlight differences in terms of CE between ideas generated by participants who used the Circular Economy Deck and those who did not.
This evaluation has only begun and there are certainly many opportunities for development. The fundamental problems were found in figuring out how to evaluate in scientific terms the degree of CE of the idea.

To solve this problem, it was decided to use the values on the Circular Economy Deck by evaluating whether the strategies were considered in the development of the innovative product idea presented in the IS. To evaluate the strategies and thus the cards on the Circular Economy Deck actually used in the development of the IS, a questionnaire was presented to four CE experts (Appendix E).

These four experts completed the questionnaire for evaluating each IS generated. Each of the presented innovative helmet ideas was described to the four experts and, through a Google Form, they have been asked to evaluate which strategies are the most impactful for developing the product idea and can choose as many strategies as they think participants have used for each idea.

Below the results are presented.

Table 13 Results of the IS (created from participants who have used Circular Economy Deck) evaluated by the CE experts.

	Rate	Standard Deviation
1st IS (using Circular Economy Deck)	4,42	0,27
2nd IS (using Circular Economy Deck)	3,21	0,58
3rd IS (using Circular Economy Deck)	4,25	0,16
4th IS (using Circular Economy Deck)	4,25	0,16
Average	4,03	0,29

Table 14 Results of the Idea Sheets (created from participants who have not used Circular Economy Deck) evaluated by CE experts.

	Rate	Standard Deviation
5th IS (without using Circular Economy Deck)	2,51	0,65
6th IS (without using Circular Economy Deck)	4,32	0,58
7th IS (without using Circular Economy Deck)	3,81	0,23
8th IS (without using Circular Economy Deck)	3,22	0,16
Average	3,40	0,41

Table 13 presents the results of the IS created with the Circular Economy Deck, while Table 14, the results of the IS created by participants who did not use it. The value presented in the Rate column has been computed after asking each expert which strategies they think have affected the product presented in the IS and which have not. As it is possible to read from Table 13 and Table 14, the results present a high Standard Deviation.

From the data collected in these Tables, it is possible to note that the average for IS created implementing the Circular Economy Deck is higher than the one implemented without using the Circular Economy Deck and that the Standard Deviation is lower. This latter information is positive and in line with the study proposed but to fully understand whether the product presented in the IS idea has an impact on CE and sustainability, LCA studies would also need to be implemented. Although experts have knowledge about LCA, for now, they have not used a specific tool to evaluate the IS generated. In the future, it is necessary to find an optimized way of evaluation that considers both CE strategies and the product life cycle and its supply chain.

Synthesis

The results of a survey on the usage of the Circular Economy Deck tool among Master students indicate a better understanding and application of CE strategies. The participants reported feeling more capable of proposing innovative products with a focus on CE opportunities, and the relationship between CE and AM was clarified. The top three CE strategies identified by the students were Reuse, Repair, and Recycle. The AM opportunities with the highest correlation to CE strategies were non-assembled mechanisms, material choices, segmentation, and objects from 3D scans, while multi-materials, embedded components, and infilling were less related. Overall, the results confirm the strong link between AM and CE strategies, the effectiveness of the research approach to empower circular aspects during the EDS of production and the students provided positive feedback on the tool.

Moreover, it has been tried to evaluate the degree of CE of the ideas. To address this issue, values on the Circular Economy Deck were used to evaluate whether the strategies were considered in the development of the innovative product idea presented in the IS. Four CE experts were presented with eight innovative helmet ideas and asked to evaluate which strategies were most impactful for developing the product idea. The experts were asked to choose as many strategies as they thought the participants had used for each idea using a

Google Form. The results show a high standard deviation, but the average for the IS created using the Circular Economy Deck is higher than the one without, and the standard deviation is lower. While this is a positive sign, LCA studies would be necessary to fully understand the impact on CE and sustainability. Currently, experts lack a specific tool to evaluate the IS generated, but an optimized evaluation tool that considers both CE strategies and the product life cycle and its supply chain is necessary for the future.

In conclusion, the results show the validity of the proposed tool and open the horizons to new areas of research. First, one can understand how to evaluate IS in more detail and how to compare them with each other from a CE perspective. Moreover, one can think about creating different decks for different areas of production, for example thinking about how to improve the link between AM and CE on the cards themselves.

6

CONCLUSIONS AND FUTURE WORKS

The aim of this thesis was to bridge the current knowledge gap between CE-related design theory and practice, investigating how the CE concept is currently interpreted and exploring what knowledge, tools, and strategies might further support design for a CE in practice. In addition, the thesis desired to investigate the role of AM as an important production system for empowering CE. To address these aims, three research questions have been formulated and proposed in Chapter 1.

To answer the research questions, which refer to the understanding of how CE is currently interpreted and how designers can improve the awareness of CE concepts during the design phase of product development and regarding the relationship between AM, CE, and EDS, a literature review has been conducted. First, this work discusses the concept of CE and its potential benefits for product design and development. The integration of AM and CE can bring benefits such as personalization, cost reduction, and improved material quality control in the EDS of product development. However, there is a lack of environmental and lifecycle considerations in the curriculum for EDS and designers face challenges in incorporating AM into their design process. The thesis highlights the importance of Design for CE and the Augmented Design with AM Methodology (ADAM2) tool in promoting creativity and sustainable production practices.

As a result of the literature review, the focus of the thesis was to investigate whether the concepts of CE can be effectively integrated into the EDS of product development. The aim was to explore the potential of using a new tool, called the Circular Economy Deck, which was proposed and created during the six months of research at Arts et Métiers ParisTech. The Circular Economy Deck is a tool that can be used to increase awareness and understanding of CE concepts in the context of product development.

Overall, the thesis aimed to contribute to the existing knowledge on CE in the EDS of product development by investigating the potential of using the Circular Economy Deck tool to promote and integrate CE concepts into the product development process. By doing so, the thesis sought to provide insights into how organizations can adopt and implement CE principles in their product development processes to promote sustainable and responsible product design.

After having presented the methodology and justified why it has been chosen Card Deck as a tool for empowering creativity during the EDS of product development, the Circular Economy Deck has been tested. The preliminary results of this pilot study conducted with a group of master's design and engineering students suggest that the Circular Economy Deck is effective in supporting the exploration of CE concepts and facilitating the ideation of eco-products. Moreover, the study showed that by introducing concepts and tools related to AM during the testing phase, it was possible to improve the student's understanding and awareness of AM's potential applications in the CE field.

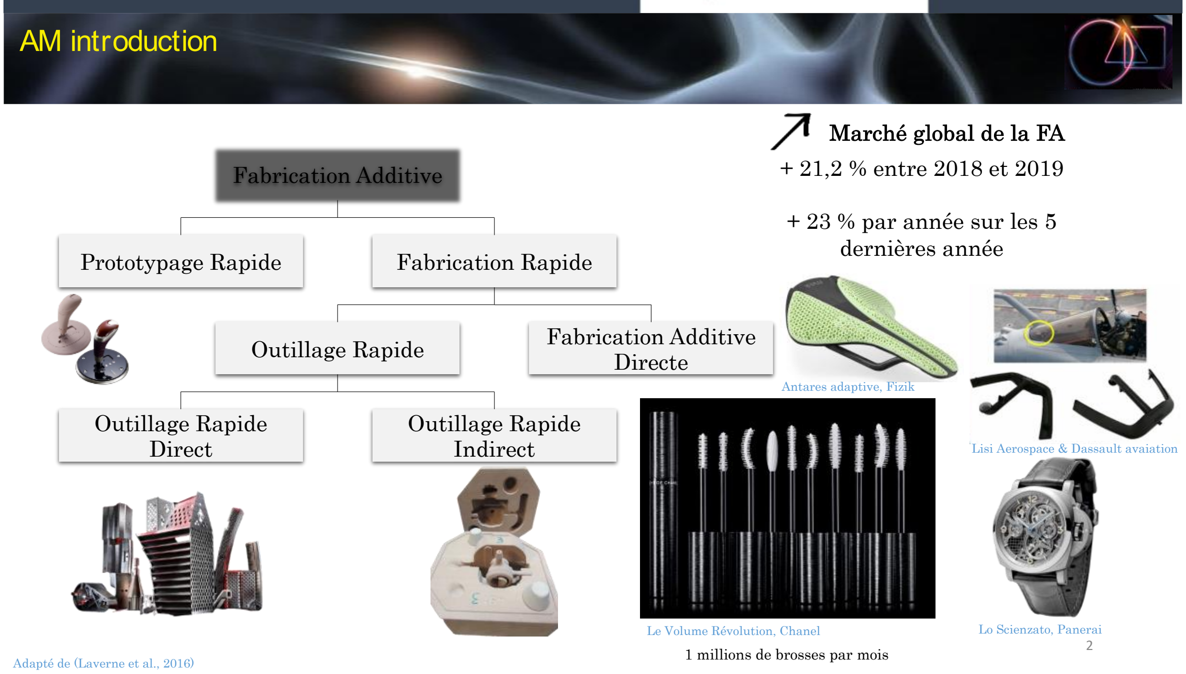
However, the study's scope is limited due to the small number of students involved in it. Therefore, future research is essential to validate and expand these findings by testing the tool with more groups of engineering students and later in companies. By doing so, researchers can gain a better understanding of the Circular Economy Deck's effectiveness in different contexts and industries.

Furthermore, future research can focus on developing sector-specific versions of the Circular Economy Deck. For example, a customized version for Industry 5.0, biotech firms, green buildings and constructions, sustainable agriculture and food systems, and other similar companies can be developed. By creating sector-specific versions of the tool, it can be better tailored to the specific needs and challenges of different industries, thereby enhancing its overall effectiveness and usefulness.

Finally, it is essential to continuously update the tool with new strategies and insights as the understanding of CE concepts and their applications in various industries continues to evolve over time. By doing so, researchers and practitioners can ensure that the Circular Economy Deck remains relevant and effective in promoting sustainable practices in product design and development.

APPENDIX A

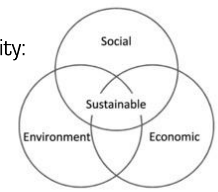
Some slides of the Power Point Presentation used on the 2nd of December 2022, before the creativity session.

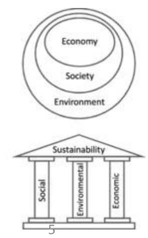


Circularity introduction

What is sustainability?

- Terms "sustainability" and "sustainable development" are closely related and often used synonymously
- Most quoted definition: “sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (UN World Commission on Environment and Development, 1987)
- Three different areas (also called dimensions or pillars) of sustainability:
  1. Environmental
  2. Social
  3. Economic





Agenda

Circular Economy Deck

- This study proposes a Circular Economy Deck : a card deck-based tool that can help designers to analyze, ideate, and develop the circularity potential in their projects. The tool is based on a literature review of circular- oriented innovation principles and strategies to realize it.
- The principles are organized according to the intended circular strategy outcome that they pursue (narrow, slow, close, regenerate), and one of the 10R strategies that each card is representing.

10

Circularity Economy Deck

Circular Economy Deck

Circular Economy Deck

How to use the cards?

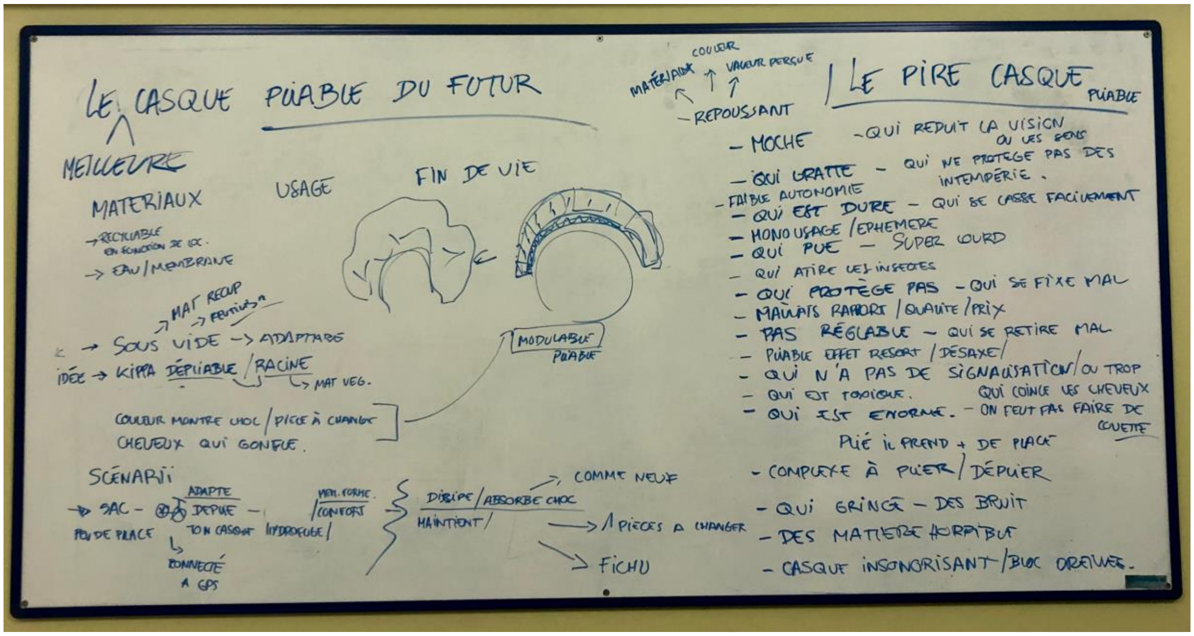
- Each card represents a strategy on which it is important to be focused on.
- The power of the card is the circular economy score. In each card, the effects that each strategy has in terms of Life Cycle Assessment have been explained thanks to the symbols under the title.
- The higher number of cards you keep in consideration for the ideation of the product in your creativity session, the higher the level of circularity reached.

REDUCE

- **Definition**: Increase manufacturing efficiency of the product or consume fewer natural resources and materials
- The idea to **make the same** (ideally more) **with less** is the backbone of the productivity mindset.
- **Example**: automating production processes or using a lower level of external inputs such as energy or more efficient raw materials consumption. 3D-printed products are designed without molds, so they require less material.

APPENDIX B

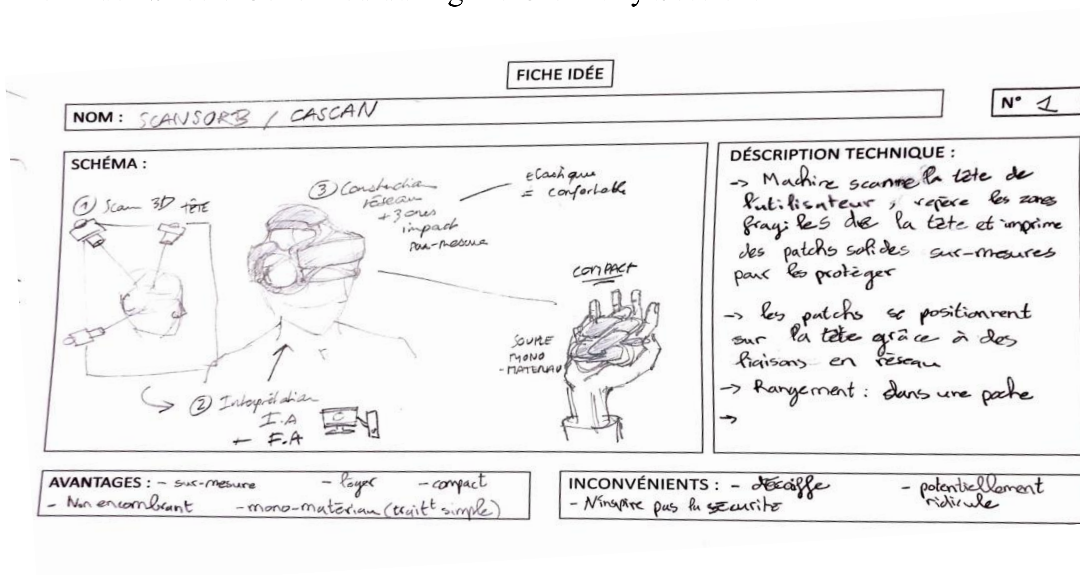
Pictures of the Creativity Session conducted on the 2nd of December 2022 in the LCPI in Paris.



LE CASQUE PLIABLE DU FUTUR
MEILLEURE
MATERIAUX
USAGE
FIN DE VIE
→ RECYCLABLE
EN FONCTION DE LOC.
→ EAU / MEMBRANE
MAT RECUP
SOUS VIDE → ADAPTABLE
IDÉE → KIPPA DÉPLIABLE / RACINE
MAT VEG.
MODULABLE
PLIABLE
COULEUR MONTRE CHOC / PIECE À CHANGER
CHEVEUX QUI GONFLE.
SCÉNARII
→ SAC –
PEU DE PLACE
ADAPTE
DEPLIE
TON CASQUE
CONNECTÉ
A GPS
HYDROFUGE /
CONFORT
DISSIPE / ABSORBE CHOC
MAINTIENT /
COMME NEUF
PIECES A CHANGER
FICHU
COULEUR
MATÉRIAUX
VALEUR PERÇUE
– REPOUSSANT
LE PIRE CASQUE PLIABLE
– MOCHE
– QUI REDUIT LA VISION OU LES SENS
– QUI GRATTE
– QUI NE PROTEGE PAS DES INTEMPÉRIE.
– FAIBLE AUTONOMIE
– QUI EST DURE
– QUI SE CASSE FACILEMENT
– MONO USAGE / EPHEMERE
– QUI PUE
– SUPER LOURD
– QUI ATIRE LES INSECTES
– QUI PROTÈGE PAS
– QUI SE FIXE MAL
– MAUVAIS RAPPORT / QUALITE / PRIX
– PAS RÉGLABLE
– QUI SE RETIRE MAL
– PLIABLE EFFET RESORT / DÉSAXE /
– QUI N'A PAS DE SIGNALISATION / OU TROP
– QUI EST TOXIQUE.
QUI COINCE LES CHEVEUX
– QUI EST ENORME.
– ON PEUT PAS FAIRE DE COUETTE
PLIÉ IL PREND + DE PLACE
– COMPLEXE À PLIER / DÉPLIER
– QUI GRINCE – DES BRUIT
– DES MATIERE HORRIBLE
– CASQUE INSONORISANT / BLOC OREILLES.

APPENDIX C

The 8 Idea Sheets Generated during the Creativity Session.



FICHE IDÉE

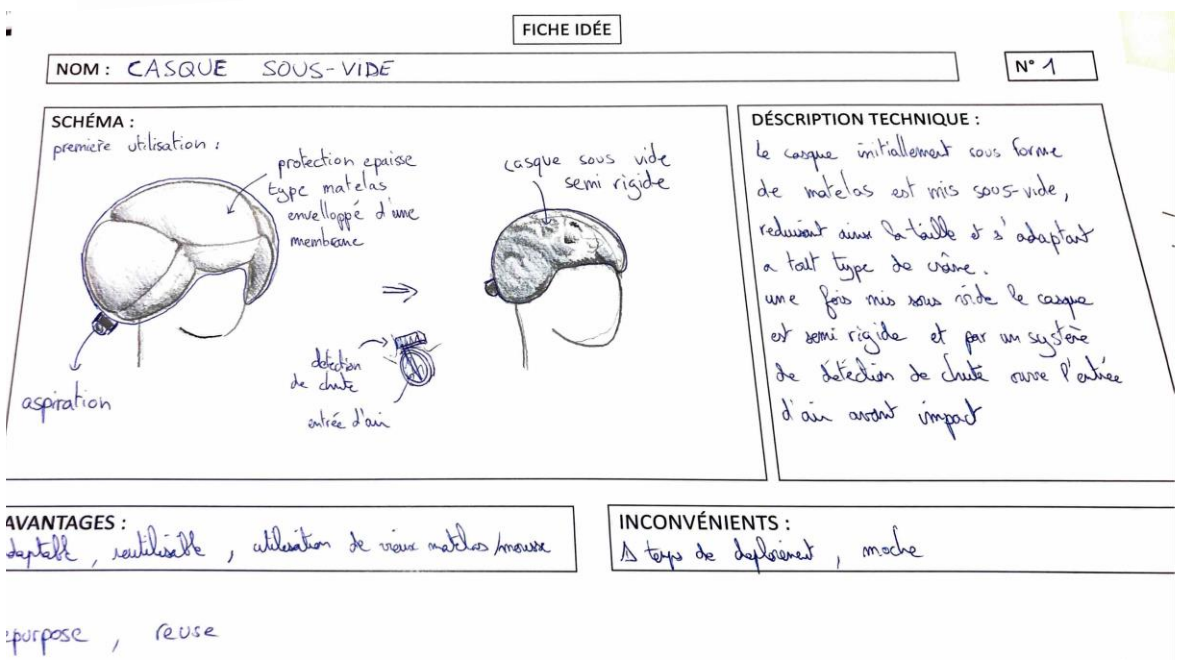
NOM : SCANSORB / CASCAN | N° 1

SCHÉMA :

DÉSCRIPTION TECHNIQUE :
-> Machine scanne la tête de l'utilisateur, repère les zones fragiles de la tête et imprime des patchs solides sur-mesures pour les protéger
-> les patchs se positionnent sur la tête grâce à des liaisons en réseau
-> Rangement : dans une poche
->

AVANTAGES : - sur-mesure - léger - compact - Non encombrant - mono-matériau (trait^t simple)

INCONVÉNIENTS : - décoiffe - potentiellement ridicule - N'inspire pas la sécurité



FICHE IDÉE

NOM : CASQUE SOUS-VIDE | N° 1

SCHÉMA :

DÉSCRIPTION TECHNIQUE :
le casque initialement sous forme de matelas est mis sous-vide, reduisant ainsi la taille et s'adaptant a tout type de crâne. une fois mis sous vide le casque est semi rigide et par un système de détection de chute ouvre l'entrée d'air avant impact

AVANTAGES : daptable, réutilisable, utilisation de vieux matelas/mousse

INCONVÉNIENTS : Δ temps de deploiement, moche

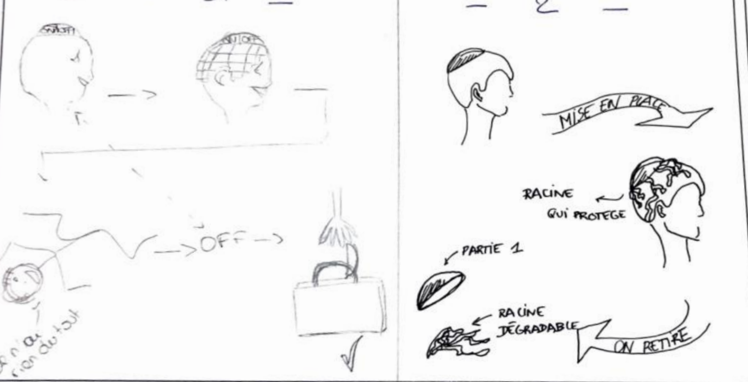
epurpose, reuse

FICHE IDÉE

NOM : KIPPA DEPLIABLE - 2 versions

N°

SCHÉMA : — 1 — — 2 —



DÉSCRIPTION TECHNIQUE :

— 1 —

L'utilisateur place la petite "kippa" sur le sommet de sa tête et appuie sur "ON". Le casque se déplie alors en s'adaptant parfaitement à la taille de l'utilisateur. Le matériau est rigide et capable d'absorber les chocs. A la fin l'utilisateur appuie sur "OFF" et range ce dernier dans son sac.

— 2 —

L'UTILISATEUR PLACE LA "KIPPA", DES RACINES SE FORME, À LA FORME DE SON CRANE.

FIN D'UTILISATION ON UTILISE LES RACINES POUR ENGRAI ET PLANTE

AVANTAGES : — 1 — Peu de places, solide, léger | — 2 — DÉGRADABLE

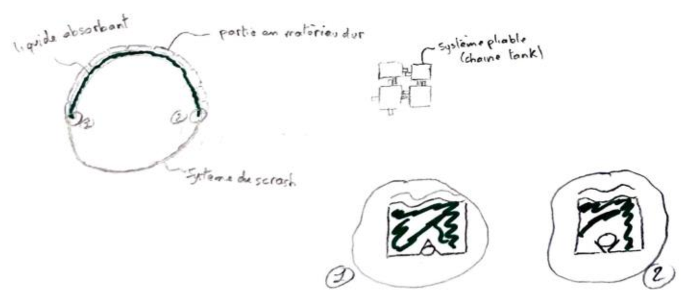
INCONVÉNIENTS : — 1 — ne va pas aux gens qui ont trop de cheveux | — 2 — RACINE QUI POUSSE VITE ? CHOC ?

FICHE IDÉE

NOM : Le casqu"eau"

N°

SCHÉMA :



DÉSCRIPTION TECHNIQUE :

casque qui contient un liquide absorbant non chimique qui lors d'un choque pas trop violant le liquide obsobe et reste dans la membrane. Si le choque est trop violant, le liquide absorbe mais si la pression est trop elevé dans la membrane, le liquide s'échappe par l'orifice ①. (systeme de claper anti-retour)

Lorsqu'il y a plus de liquide, on effectue la recharge de celui-ci par le trou ②

AVANTAGES : léger, très pliable, rechargeable

INCONVÉNIENTS : avoir du liquide sur soi

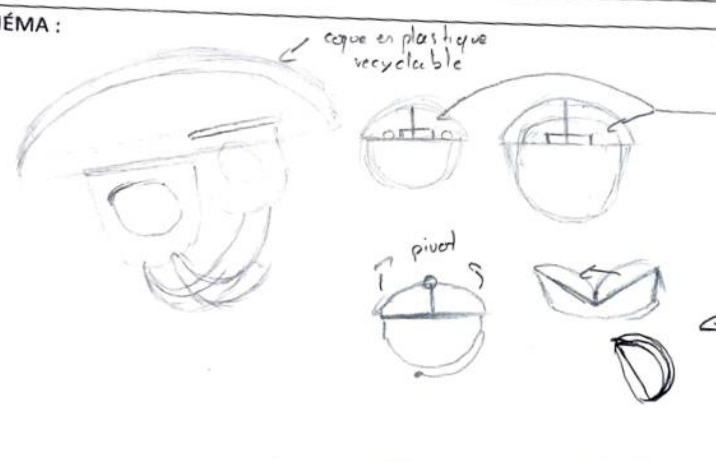
FICHE IDÉE

C

NOM : Casque plast pièce interchangeable recyclable

N° 02

SCHÉMA :



DÉSCRIPTION TECHNIQUE :

batterie USB C, signalisation connecté au velo / gps pliable/souple

Casque se replit sur lui meme comme une double peau ex : bouteille en plastique

AVANTAGES : gain de place connecté
personnalisable

INCONVÉNIENTS : composant peu / pas recyclabe

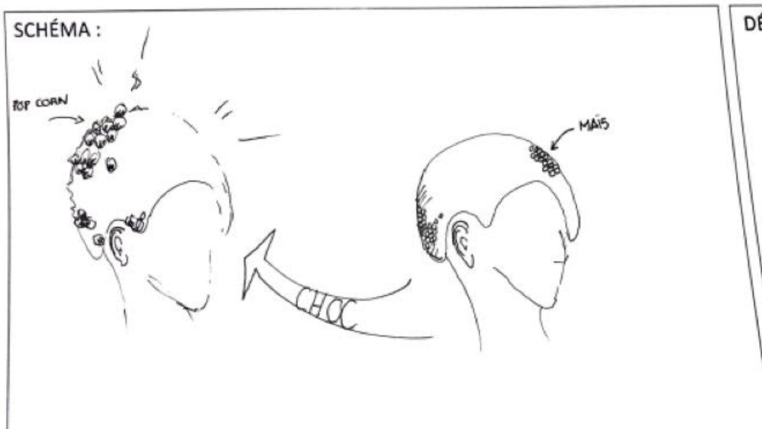
FICHE IDÉE

C

NOM : POP CORN

N°

SCHÉMA :



DÉSCRIPTION TECHNIQUE :

→ POP CORN QUI CHAUFFE ET PETE AU MOMENT DE L'IMPACT

→ GRAIN DE MAÏS DANS UNE MEMBRANE

IMPACT

FOUR CHAUFFE

POP CORN

IMPACT MOINDRE

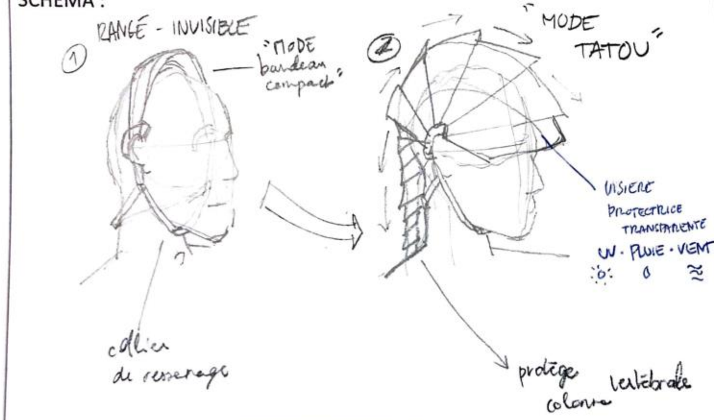
AVANTAGES : éviter un impact violent → repousser grâce au craquage du maïs. Léger

INCONVÉNIENTS : Le chauffage ne doit pas déranger l'i

FICHE IDÉE

NOM : CASQUE TATOURISQUE — **N°** 2

SCHÉMA :



DÉSCRIPTION TECHNIQUE :

-> L'utilisateur porte un bandeau / serre-tête qui se développe en casque et protège le crâne et la colonne vertébrale de façon télescopique comme un tatou

-> Il se range sous forme de bandeau

AVANTAGES : - Grande protection

INCONVÉNIENTS : - Pas simple à déplier
- Pas pratique à ranger car pas plat

FICHE IDÉE

NOM : ~~Non casse tête~~ SCANSORB / CASCAN — **N°** 1 Bis

SCHÉMA :

(VOIR FICHE 1)

DÉSCRIPTION TECHNIQUE :

Un casque avec la forme de voronoi (generative design) qui est fabriqué avec un gel type non-Newtonien comme D30.

La forme de la tête est scanné en 3D. Avec l'intelligence artificielle et GD, on arrive à trouver les poins critiques de la crane d'utilisateur.

Fabrication par 3D avec le matériau D30 en utilisant le de l'optimisation topologique.

Les parties se détacte et se c dans un tas.

AVANTAGES : la précision sur la sécurité par l'utilisateur

INCONVÉNIENTS :

APPENDIX D

A sample of the questionnaires that were filled in by the participants.

Please, in the table below, select (X) which cube is the most inspiring for each strategy. Multiple choices are allowed.

CE STRATEGIES \ AM CUBES	Segmentation	Embedded components	Internal Channels	Infilling	Auxetics structure	Material choices	Multi-materials	Freeform shapes	Objects from 3D scans	Microstructure variation	Texture	Monoblock	Topology optimization	Non assembled mechanisms
REFUSE														
RETHINK						1			3					2
REDUCE						2							1	
REUSE	2								1					
REPAIR	2								1					
REFURBISH														
REMANUFACTURE	2								1					3
REPURPOSE	2								1					3
RECYCLE														
RECOVERY								1		2	3			

I used the **Circular Economy Deck** during the creativity session:

YES	NO
	X

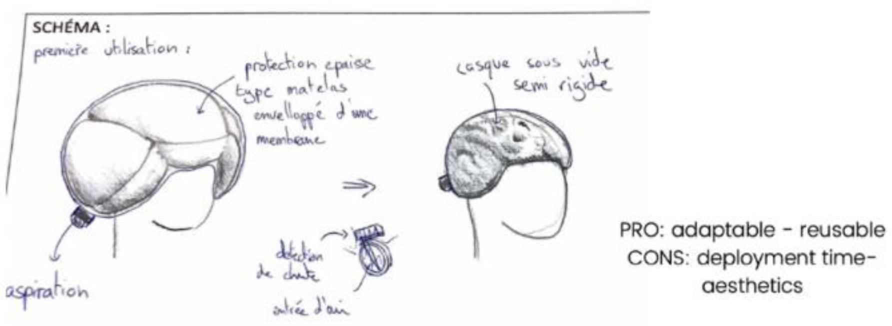
	Totally disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Totally agree
I feel more able to explain the main concepts of Circular Economy						X
I think that I have better understood the relation between Circular Economy and Additive Manufacturing	X					
I feel capable of proposing ideas of the innovative object being more focused on the opportunities of the Circular Economy			X			
I feel able to explain and exploit all the pursuable strategies for Circularity		X				
I think I have mastered the Circular Economy strategies and their power	X					

APPENDIX E

A sample of the questionnaires that were filled in by the CE experts.

You are asked to evaluate which strategies are the most impactful for developing the product idea below showed. You can choose as many strategies as you think they have used for each idea. **Multiple choices are allowed.** *

2nd Idea Generated:



The helmet is shaped like a mattress and vacuum-packed to fit all head types. Once opened, the helmet is semi-rigid and a fall detection system monitors the air intake before impact.

- ☐ REFUSE: Make the product redundant or offer the same function in a radically differe...
- ☐ RETHINK: Make product use more intensive and efficient
- ☐ REDUCE: Decrease Raw material usage
- ☐ REUSE: Employ second-hand products
- ☐ REPAIR: Repair of the defective products to be used with their original function
- ☐ REFURBISH: Restore an old product and bring it up to date
- ☐ REMANUFACTURE: Utilize leftover product components to create a new item that ser...
- ☐ REPURPOSE: Use discarded products or their part in a new product with a different f...
- ☐ RECYCLE: Convert waste into reusable material
- ☐ RECOVERY: Incineration of material with energy recovery

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