Additive Manufacturing as an opportunity for supporting sustainability through implementation of circular economies

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Abstract: As changes are automatic while progress is not, technology improvements in manufacture need to find their room within market requirements. Among the challenges manufacturers have to face with, there is the need to approach a multifaceted context. Additive Manufacturing is considered one of the most effective technology with the potential to give proper industry-side responses to markets, fulfilling a long-term sustainable perspective. Layered fabrication may lead to structural changes both in economics and societies and may fill the missing tie to foster the spread of circular systems towards the realization of effective circular economies. There is a widespread interest for manufacturing to shift from linear to circular systems, where biological and technical saves are possible. This paper thus aims to frame Additive Manufacturing, one of the most game-changing technology of nowadays societies, into the need and characteristics of Circular Economy concept, one of the most challenging change in human progress.

Keywords: Additive Manufacturing, Circular Economy, Sustainable manufacturing, Smart manufacturing

1. Introduction

Nowadays occurring changes in manufacturing bring both opportunities and challenges and cannot be addressed with old responses, neither by business leaders nor by policy makers (Manyka et al. 2012). Technological advances allow manufacturers to follow the market trends inventing new ways of fabricating things. By far the most promising of these steps forward is Additive Manufacturing, which "seems to have moved in the hype cycle from the initial rush of enthusiasm for a technology's potential to a more evidence-based understanding of what the technology can really achieve" (Fenn and Raskino 2012). Next to the new manufacturing paradigms stays the concept of Sustainable Manufacturing (Garetti e Taisch, 2012), which is relevant for the modern competitiveness at industrial level and can be extended to a wider circular economic view. The circular economy approach addresses how biological and technical nutrients produced along the product lifecycle are managed respectively to reenter the biosphere and to recirculate at previous stages in the production system (Ellen MacArthour Fundation 2016).

Circular economies implementation is not only a necessary effort towards environmental sustainability, but also a real need to be pursued by industries to compete in the global markets and to gain competitive advantages for the next years. In fact, the economic systems have become increasingly dynamic, with a constant need of change, keeping up with the global growth and resources shortage. The expectations of those engaged in AM such as providers, users and policy makers, refer to several potential benefits compared to traditional manufacturing processes such as waste reduction, recycling of raw materials at several stages of a product lifecycle, reduction of handling and transportation activities, lower energy consumption of printers, use of biodegradable materials and ease of decommissioning and disposal of the products (Gleber et al. 2014)(Garret 2014). In this concern, additive manufacturing has shown to embody concrete potentialities (Petrovic et al. 2011). Along with discussing these aspects in details, this paper aims to give a better understanding on how AM can be the opportunity for a better manufacturing solution to enable efficiency and sustainability in a circular economy frame. The paper is structured as follows. In section 2 a brief explanation about linear and circular systems is given. In section 3 the implementation of circular economies trough additive manufacturing is discussed. Section 4 analyzes characteristics and aspects of sustainability of additive manufactured based circular economies. In section 5 eventually, final considerations and conclusions are given.

2. Linear and circular systems

Nowadays modern economic systems can be classified according to two main paradigms: linear systems and circular systems.

The linear model is an archetype designed on a static view of production and logistic flows that goes from the raw materials provision and transformation, until the finished product dismissal.

This aspect constitutes a limitation to the whole economic model, which results in the long run ineffective under the perspective both of economic and environmental sustainability. As a matter of facts, once goods are fully consumed and they come to the last phase of their life cycle, they turn into waste and new material has to enter the system as the cycle has to start newly (i.e. mining, production, consumption and disposal). This kind of resources usage follows the "cradle to grave" approach, which begins with the creation of a good (cradle), and ends with its dismissal, without any opportunity to be further exploited in other ways (grave) (Fig.1). Therefore, these flows are unidirectional along the value chain and limited as they enter the system once. Due to the limitation in the exploitation of the flows, this paradigm is not sustainable over a long time.

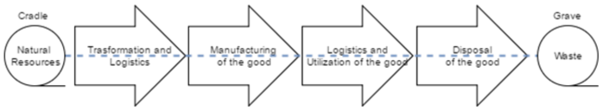

Fig.1- Linear System

On the contrary, circular systems provide for a more efficient use of resources, where flows are not static and unidirectional, but fall circularly in the upstream stages of the production system.

This paradigm is also known as "cradle to cradle" approach, where the input representing the incoming resources for each stage of the production process are integrated with the flows of materials and energy already used in downstream stages of the chain that have the characteristics and the potential to be reused within the system (Fig. 2).

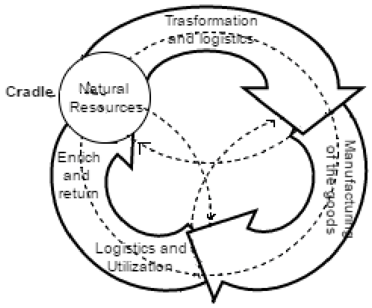

Fig.2 Circular System

The materials and energy required along the life cycle of a product are not completely depleted as in linear systems (Yuan et al. 2006), but opportunities of reuse are sought within the system to make it more sustainable.

Circular systems allow to extend the final phases of the product life cycle, for example through a different reuse of the resources, and it is also possible to stretch the entire cycle thanks to the increase of the exploitable efficiencies of each single phase of the process, due to the replenishing of circular flows. This approach can lead to numerous advantages, both in the industrial and in the commercial perspective as to the final consumer point of view, these potentialities can be exploited in terms of maintenance and product recycling.

This approach also focuses on understanding how materials flow can have a positive impact on the environment, rather than assessing an intervention of reduction of negative impacts on it. The objective is to have an integrated process between technical and biological flows and an integrated management by minimizing or eliminating waste (Ellen MacArthour Fundation 2016). The ability to reuse materials, tools and equipment into the production circuit originates a mechanism that drives an increasing number of companies to design products on the assumption that each input to the production system will be reused somehow without ever turning into a waste or something that has to be unpacked. Improvements in efficiency and effectiveness that can then be reached are numerous and different, depending on the process phases within the production system has been referring to.

According to Ellen MacArthur Foundation, the circular economy "is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" (Ellen MacArthour Fundation 2016). What is important in the transition from a linear to a circular economy is the creation of a sustainable system and the ability to capture the value that would normally be lost with a linear approach, thus resulting in an economic loss in the long run. In a circular economy, opportunities such as the reduction of time and energy consumption along the production process, the product use, design and the end of life can be attracted and captured in the view of an economic and sustainable growth (Ellen MacArthour Fundation 2016).

3. Additive Manufacturing Technologies as a tool for implementing Circular Economies

In the previous section, it has been seen how a circular economy tries to rebuild capital, whether financial, manufacturing, human, social or natural, by managing the resources reuse inside the system.

Nowadays, several technologies are considered key enablers for relevant changes in societies and economies (Garetti e Taisch, 2012)(European Commission 2016).

Additive Manufacturing is seen by researchers and practitioners as one of these key technologies supporting the future manufacture towards mass customized, lean and flexible production (European Commission 2016). Additive Manufacturing refers to a set of production technologies dedicated to the manufacture of goods through addition of material, differing from the traditional manufacturing techniques characterized by material subtraction: starting from a three-dimensional digitized file, the object is built "layer upon layer" (Petrovic et al. 2011)(European Commission 2016)(Frazier 2014). The American Society for Testing and Materials (ASTM) have proposed seven categories through which analyzing Additive Manufacturing technologies (ASTM 2012). It's not the aim of these paper to go through each AM technologies, whose dissertation is vastly addressed in literature (Gibson et al. 2010)(Horn and Harrysson 2012)(Scott et al. 2012)(Thymianidis et al. 2013) (Achillas et al. 2015).

The Additive Manufacturing Technology (AMT) allows a good integration of the technology itself and the circular economy approach, thanks to the opportunities that can be leveraged throughout the value chain: energy consumption reduction, less amount of materials used from maintenance to re-use, from the rework to recycling.

In a circular economy, modifying the digital file before processing, gives the capability to redesign and address the product to other applications (Wits et al. 2016).

With the AMT, it's talk about a virtual manufacture that comes to a physical object as the real good is not the product, but the CAD file. The opportunity to obtained a more efficient process through the adaptation of the piece to specific end-user needs through the digital file modification, such as the increase or decrease in size to facilitate the assembly or modification of the shape, easier ability to merge multiple parts into one without resorting to physical assembly, minimizing the fasteners such as screws and welds, the modification of existing parts for new applications arise the chance to exploit these advantages in an integrated optimization view.

The additive manufacturing ability to exploit circular economy potentialities by pursuing product customization could bring to the end of the generation of unnecessary stocks, typical of the static and linear economic systems. It is a more feasible prediction when two key factors are there: the interest and the improvement of the design phase, and the simplification of the related software tools, together with the opportunity for the consumers to create a bridge between the product design activities and the creation of a unique product (Giurco et al. 2014). With the additive production specific parts and components can be adjusted by the final customer, that leads on creating a smaller circular economy flow and thus optimizing the process by reducing the time of manufacture and repair. There are business models structures, such as the distributed manufacturing, that gives the opportunity to have a slimmer product design phase and the consumer can personally make the assembly if the cost and convenience factors make it feasible. This benefit opens the door to a potential local material recycling as the technology makes "on-shoring" activities achievable for the recovery of natural resources that lead to the realization of a circular economy loop. Another opportunity to exploit a circular economy behavior through the adoption of AMT comes from the assumption that most of the manufactured products have the chance to be repaired if they break, even if not often simple or convenient. Repairs occur as the cumulative value of the broken good and the costs to fix it is greater than the cost to produce a new good, combined with the availability of resources, machines and delivery times aligned with the market needs. Nevertheless, it is important to emphasize the difference between the repair of a product and its rework. A rework occurs when the good is affected by changes during the process, with the purpose to increase its value, while if those changes take place without a growth in value, then it is talking of a repair. The reason why organizations implement repair activities is to ensure a good supply of spare parts, increasing profitability and market share (Peattie and Seitz 2004), achieving good sustainability parameters in the management of the product end of life, enhancing both economic and environmental aspects in a circular efficiency view. This model can be achieved through the adoption of the business model described above as distributed manufacturing. The alignment of AMT and the concept of Circular Economy has to be sought into several aspects, which may contribute to the optimization of some phases within circular systems (e.g. maintenance, reuse, rework and recycling of products). Hereinafter they are presented and discussed.

1.Material savings. AMT enables to reach significant material savings due to the absence of tools and the use of the near exact amount of material needed to manufacture the product. This aspect allows to reduce or completely delete wastes and the usage of raw materials both during the design and production phases.

2.Flexible manufacturing strategies. On Demand Manufacturing. AM based production systems lead on production strategies that may support relevant minimization of transportation and logistics. Such strategies stands on:

a.on demand production of goods instead of forecasted based production;

b.distributed manufacturing, which allows to locate local manufacturing systems nearer to the specific cluster of customers.

3.Hard repair and maintenance intervention. The maintenance phase allows the achievement of further advantages in a circular economy perspective as spare parts can be additively manufactured only if the necessity arises, coming up to time, with consequent space and storage cost savings. Thus, it comes out that the chance to repair a good becomes preferable compared to the substitution of the demaged part.

4.Extended products life span. The life span of a product can increase not only due to specific technical improvements given by the technology itself but also due to the easy access to parts repair interventions instead of manufacturing new spare parts.

5.Design based economy. Barriers related to the knowledge of the product and the knowledge of the product manufacturing process can be significantly lowered thanks to additive manufacturing characteristics: parts can be directly manufactured from 3D CAD files without owning manufacturing experience; if the digital format is not available, the object can be easily scanned by means of 3D scanning techniques. In order to accomplish these changes there are some drawbacks and challenges that manufacturing companies have to take into consideration. Among all, the concurrent engineering attitude becomes a fundamental perspective, and the design phase has to be run taking care of MRO phases (Maintenance, Repair and Overhaul), which implies ease of assembly, disassembly, and repair intervention directly by the consumer, substantially driven from costs and convenience evaluations (Wits et al. 2016)

Table 1: AMTs categories – Additive food manufacturing (F.G. Sisca, C.M. Angioletti, et al. 2016)

ASTM Classification (AM processes)	Commercial	Food material

	Technological Solution	
Powder Bed Fusion	SLS	Sugar
Directed Energy Deposition	n.a. for food	n.a. for food
Material Jetting	Polyjet	n.a. for food
Binder Jetting	3D Printing – Inkjet Printing	Sugar, Protein powders
Material Extrusion	FDM	Chocolate, Pasta Dough
VAT Photopolymerisation	SL	Eggs white, package
Sheet Lamination	LOM	n.a. for food

Printing in food has been already used as 2D printing (i.e. laser marking, inkjet printing) since 90s (D. Sher 2015), while in last five years the market has assisted to inclusion of several AMTs in producing diverse foods ranging from chocolate to pasta and pizza.
The AM food system is provided with a computer controlled three axes motorized stage and material feeding system and it manipulates food layer by layer according to the design information contained in a CAD file. (Sun, Peng, et al. 2015). Food printer platform basically consists of a Cartesian coordinate system, user interface and layer by layer system mainly based on three categories: extrusion, binding, and sintering. Material Extrusion category, or hot-melt extrusion, consists of extruding hot melted material through a nozzle. It allows to obtain customized geometries, textures and food content (i.e. multiple nozzles system) (Goyanes et al. 2015). In hot-melt extrusion (i.e. Fused Deposition Modeling - FDM), hot material is pushed through a die of the desired cross section.
In Binder jetting or inkjet printing category systems, an inkjet printhead moves across a bed of powder and selectively deposits a liquid-binding material. Afterward, a thin layer of powder is spread across the section. This process is repeated until all layers are completed and unbound powder is removed. Powder bed AM systems have some potential in food printing for all applications where the shape of the raw material is given in input as powder. Such processes can be found for example in pharmaceutical applications (Ventola 2014).
Powder Bed based category (e.g. Selective Laser Sintering - SLS) comprehends processes in which a laser beam is used to bind materials together to create a solid structure. Selective laser melting (SLM) uses also a laser beam, to melt the materials together. SLM might be suitable for 3D food printing for attaching food components together. (Pallottino et al. 2016b). SLS is used currently for sintering sugar powder. Examples of above AM technologies applied to food are presented in section 5.

4. AM based circular economies towards sustainability

Even if it is true that Additive Manufacturing guarantees the savage of a good amount of materials, it is therefore not always clear from the environmental sustainability point of view whether all AMT categories underlie waste reduction (e.g. stereolithography process generates waste materials for the support structures creation). Moreover, as in AM the production process collapses in the printer, it's important to consider when thinking about resources usage the life cycle of the printer itself. In other terms complete analysis over the whole lifecycle of the additively manufactured products and AM machines have to be taken into consideration, in order to state proper quantitative sustainability gains and losses, however not always specific frameworks towards this direction are customized for AM case.
Nevertheless, it can be said that Additive Manufacturing is that kind of production that has the potential to be successful and to enable a circular and sustainable economy [21] .
If one considers the manufacture as the conversion of materials and energy in goods, the efficiency of this conversion is crucial for the generation of environmental impacts and wastes.
As in any manufacturing system, even in additive manufacturing systems economic and environmental performances are strongly related, that affects the ability to be competitive with conventional processes, at least for small and medium production volumes. The economic benefits due to the efficiency and the process improvements reachable with the design, testing and production phases are greater than the benefits resulting from the reduction in investment for the purchase of machine tools (Atzeni and Salmi 2012) . In addition, once the design phase of the part is run, the production phase starts immediately, coming out into a reduction in costs achieved by decreasing the time between design and manufacture. It can come to a higher costs reduction thanks to the modification and the flexibility of shapes and geometries that, combined with the reduction of the materials usage, result in a significant decrease in costs and amount of resources along the entire life cycle, also thanks to the fact of having lighter components in the use phase.
The energy and material efficiency can be increased through dematerialization and reduction of the consumptions within the processes; plus, the adoption of additive manufacturing technology allows an optimized reconfiguration, more localized and decentralized supply chains and business models: components and lighter subassemblies, circular flows and reduced use of resources, simplified transactions and reduction of environmental impacts.
Despite the potential increase of the recycling rate of material usage, these are not necessarily more "clean" of those used in conventional processes. The potential reduction of material is partially countered by the relative toxicity of raw materials and especially by the energy and environmental impacts deriving from the process of material transformation.

5. Conclusions

This work has showed how production and services oriented manufacturing through additive manufacturing technologies use, trying to meet the individual customer needs achieving the chance of a higher production efficiency in terms of manufacturing costs and therefore sale prices content, within a Circular Economy frame. Today, the adoption of this additive manufactured-based strategies makes extensive the use of decentralized economic systems, web-based information and communication technologies by reducing the time between the communication of customer desires and the availability of the required good.

Nowadays, companies are competing in delivering to customers functional, aesthetic, but also recyclable and energetically efficient products at competitive prices and short lead times. In today markets, customer-based production is the main trend and different challenges have been pulled by the market: from the idea of personalized products available and easily reachable on the market to the environmental sensibility that has been catching on. Covering the whole aspects concerning a product life cycle, the entire value chain changes in AM: from the supply of raw materials, the delivery of the product to the customer, till the maintenance and the recycling stages. In fact several technical peculiarities in AM products and processes imply impacts on an organizational level, which activate potential adoption of flexible manufacturing strategies (i.e. distributed manufacturing and on demand manufacturing), more customer oriented and with a low environmental footprint. The main environmental benefits allowed by the use of additive manufacturing technologies in industrial manufacturing consist on lower energy consumption of printers during the manufacturing process, ease of the decommissioning and disposal of the products, reduced waste and increased recycling rate of raw materials. In conclusions, environmental benefits up to now are qualitatively clear and logical to understand however quantitative analysis supporting these considerations are needed. First of all, it is important to find out whether the enormous benefits coming during some phases of the life cycle are able, both economically and environmentally, to exceed the criticalities coming from other phases and not yet avoidable. Moreover considering a life cycle based standpoint further investigations have to be carried on economic systems in order to show where and how AM can concretely trigger saves, both on the biological and technical flows. Therefore future works will be addressed towards the investigation of methodologies and quantitative models in order to assess how AM technologies foster the reuse of materials, tools and equipment within the shift from linear systems towards circular systems. Moreover customization of other quantitative methodologies such as LCA and Risk assessment upon real industrial cases of AM products and processes, manufacturing and adoption, will be implemented.

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