Additive Manufacturing applications within Food industry: an actual overview and future opportunities

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Abstract: The food sector is one of the major economic sectors in Europe and beyond and produces nutrition for the world population. Food industry has a unique role in all countries economy as it is essential to people lives. In Europe it is the largest manufacturing sector in terms of value added, turnover and employment. On the other hand, several worldwide economic-social-technological trends are pushing organizations to embrace innovation as an integrated part of their corporate strategy, and to offer customized products tailored to market targets need. Embracing innovation became strategic in order to create a sustainable competitive advantage and to stay ahead of the competition in every industry, even in food one. Today, among all the most cutting-edge technologies, Additive Manufacturing (AM) has the potential to develop business paradigms to face an ever changing demand. AM comprises a group of technologies whose initial inception occurred over thirty years, characterized by a layer upon layer production directly from Computer-Aided Design (CAD) data. Over the past few years AM development has increased exponentially and has expanded to include new areas of research. Within all the innovative applications, one of the most promising under respect of social impacts and progress, has proved to be the technological application in the food industry. This scientific work aims at finding out potential touching points between additive manufacturing technologies and food market, either consumer and industrial, focusing on the actual and future applications.

Keywords: 3D Printing, Additive Manufacturing, Food, Innovation, Smart Technologies

1. Introduction

The food sector is one of the major worldwide economic industry (CIAA 2009), which produces key nutrition for the world population (Regmi & Gehlhar 2005). Food sector, widely recognized for its innovation content, is the largest European manufacturing market in terms of value added, turnover and employment rate (FoodDrinkEurope 2012). Companies operating in food industry face many challenges in managing their products and competing in the industry (Pinna et al. 2016). In fact, according to Kalypso (Kalypso 2010), Siemens (Siemens 2011) and Oracle (Oracle 2008), the Food industry has to contend with different challenges, most of which refer to: (i) Retail consolidation, (ii) Ineffective innovation, (iii) Increasing regulatory requirements and unclear regulations, (iv) Empowered consumers, (v) Increasingly complex global supply chains, (vi) Sustainability, (vii) Time to Market. National governments and institutions agendas focus on this theme that is under the light of technological and economic studies from research community and industries as well.

All these typical issues are positioned within a more general worldwide frame in which global markets are increasingly being driven by demand for product customization, shorter product life cycles and increasingly customers awareness, resulting in a greater uncertainty in market demand (F.G. Sisca, M. Fiasché, 2015). Among all the key enabling technologies (KET) (European Commission) pushing industries towards these transformations, Additive Manufacturing (AM) has the potential for a social-economic change by moving manufacturing away from mass production to mass customization and distributed manufacturing (Achillas et al. 2015). AM refers to a group of technologies, whose first appearance occurred in the early 80s (Sisca, Angioletti, et al. 2016.) and characterized by a layer upon layer production based directly from Computer-Aided Design (CAD) data. Since its inception, AM has demonstrated a disruptive potential to develop new business paradigms, customized products and more reactive and agile supply chains (Abbink 2015).

Recently, several researchers and practitioners have followed the idea that even the food sector can use the peculiarities offered by the technology (e.g. geometry freedom, multi-material) (Godoi et al. 2016a; Pallottino et al. 2016a) to solve the challenges discussed above. Moreover, specific sectors may receive turning contribution from Additive Manufacturing Technologies (AMT) and, most likely, will be the engines for the developing of AMT in food applications (e.g. space and defence).

This scientific work aims at finding potential touching points between additive manufacturing technologies and food markets (either consumer or industrial), focusing on the actual and future applications. It provides an updated state of the art of the AMT in the food sector, following rigorous use of the terminology and classification along the whole business value chains. Detailed discussion on characteristics, fulfilled needs, benefits; specific technologies for each real application is presented as well. The paper is structured as follow: Section 2 presents a short background. Section 3 describes all the AMT used in the food sector, while section 4 presents and discusses the available food materials. Section 5 explores the current applications of AM in the food sector. The advantages of the impact of food AM are then analysed in section 6, followed by the indications of the barriers and critical factors for the food AM diffusion at large scale so far. Eventually in section 7 final consideration and future trends of the AM in the food sector will be given.

2.Background

The first examples of Additive Food Manufacturing (AFM) dates back to 2007 when researchers from Cornell University introduced a syringe equipped version of an open source extrusion based AM machine (i.e. Fab@home) (Periard et al. 2007). Since then, a number of companies and organizations have designed machines and offered different applications ranging from personalized pieces of pasta to chocolate (Halmes & Pierreu n.d.). Many studies have been carried out in order to fine tuning the machine design and adapt AMT to the design of food construct (Diaz, J.V., Van, B.K.J.C., Noort, M.W.J., Henket, J., Brier 2014; Diaz et al. 2015; Grood, J.P.W., Grood, P.J., Tillie 2013; Hao, L., Seaman, O., Mellor, S., Henderson, J., Sewell, N., Sloan 2010; Hao, L., Mellor, S., Seaman, O., Henderson, J., Sewell, N., Sloan 2010; Sol et al. 2015; Serizawa et al. 2014; Schaal 2007). Some commercial solutions are now available on the market for both professional and consumer purposes: Foodjet by De Grood Innovations, Foodform 3D by RIG, ChefJet and CocoJet by 3D Systems, Foodini by Natural Machines, Choc Creator by Choc Edge, Imagine3Dprinter by Essential Dynamics, Replicator by Makerbot (Sun, Peng, et al. 2015) (Lipton et al. 2015).

3. Additive Manufacturing Technologies for Food

The term Additive Manufacturing refers to processes which, compared to the traditional technologies (i.e. subtractive and formative (Thymianidis et al. 2013), produce layer by layer physical objects directly from Computer-Aided Design (CAD) data. AM is classified in seven categories by the ASTM F24 committee of AM that comprehend all processes and commercial solutions used for layer by layer manufacturing in whatever applications, either in consumer and industrial markets. AM comprehends a varied group of technologies, included 3D Printing (3DP) which is, among the others, one of the technologies, whose basic characteristic is creating net shapes by adding material layer-by-layer. The corresponding application fields can vary and just a few are employed in food sector to date0. Table 1 shows the correspondences among ASTM categories and commercial solutions available in the market. Indications on the material used in food is showed as well.

AM process starts from the design in the form of a computerized 3D model, which can be directly transformed into a finished product through several phases, without the use of molds, additional fixtures and cutting tools 0. In fact, behind the well-known denomination of AM, there is such a variety of different manufacturing processes that researchers cannot refer to as a whole (F.T. Piller et al., 2012).

Table 1: AMTs categories – Additive food manufacturing

ASTM Classification (AM processes)	Commercial Technological Solution	Food material
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

(F.G. Sisca, C.M. Angioletti, et al. 2016)

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. Material for food

In actual applications the material most used for AMTs are cake frosting, chocolate, processed cheese, dough, hummus, starch (for support) and sugar (in powder). Ice cream and butter are started to be used as well (Periard et al. 2007). According to Sun et al., the available materials for Additive Food Manufacturing (AFM) can be classified into three categories: natively printable, not traditionally printable and alternative food. Natively printable materials have different taste, nutritional value, and texture. Some of them are stable enough to hold the shape after deposition/extrusion, while others may require a post-cooking process (Vesco et al. 2009). Non-printable traditional food are materials largely consumed by people every day and they need addition of hydrocolloids to be processed. Some solid and semisolid foods have been manipulated to become printable. After the AM process, they go through a cooking processes, such as baking, steaming, or frying (Sun, Zhou, et al. 2015). Alternative ingredients such as insects, algae, fungi, seaweed lupine may be novel sources for protein and fiber allowing to develop healthier food products than with the traditional cooking (Sun, Peng, et al. 2015)(Pallottino et al. 2016a). Moreover, residues from agricultural and food processing can be transformed in biologically active metabolites, enzymes, and food flavour compounds (Silva et al. 2007; Nikitina et al. 2007). Such a material may constitute a sustainable and eco-friendly AM material source (Sun, Zhou, et al. 2015).

Table 2 shows a summary of materials, with their characteristics product examples and the related technology used for their production.

Table 2: AMT - materials properties

Material	***Natively Printable Materials***	***Non-printable Traditional Food Material***	***Alternative Ingredients***
Product application	Hydrogel, cake frosting cheese, hummus, chocolate	Rice, meat, fruit, vegetables	Extracted from algae, fungi, seaweed, lupine, and insects
AMT	Extrusion	Extrusion, adding hydrocolloids	Extrusion

(Sun, Peng, et al. 2015; Sun, Zhou, et al. 2015)

One of the critical challenges in the 3D food printing field has been to align food grade materials with printing processes. (Godoi et al. 2016a). According to Godoi et al., three food materials property are suggested for the rational design of 3D food structures: printability, applicability and post-processing.

Printability relies on how material properties enable handling and deposition, and on the capability to hold its structure post-deposition;

Applicability means in terms of building complex structures and textures, and customized nutritional value. The applicability of AM technology is also ruled by material properties.

Post-processing implies that 3D food construct should be able to resist (in terms of shape and nutritional value) to post-processes activities, such as, baking in an oven, being cooked by immersing in boiling water or deep frying. In the pursuit of a cooking-resistant structures, an accurate selection of materials with appropriate physical-chemical, rheological and mechanical properties are essential.

Proper knowledge of the essential constituents of food (carbohydrates, proteins and fat) and how their properties are correlated with the choice of the proper AMT is critical to guarantee the target quality of the end-use product. (Godoi et al. 2016a)

Food materials should be fluid (liquid or powder) during deposition and also should support its structure during or after the deposition (Godoi et al. 2016a).

Fluidity is achieved by plasticization and melting. In a multicomponent system, variations in the fraction of proteins, carbohydrates and fats will affect the melting behaviour, glassy state and plasticization of the food-materials during liquid-based and powder based 3D printing processes (Bhandari & Howes 1999; Bhandari & Roos 2003; Haque & Roos 2006; Roos 2010; Slade & Levine 1994).

5. Actual Applications

Currently exploited applications in AFM regard content customization, shape customization, rapid prototyping, rapid tooling and bio-printing. About content customization, Foodini by Natural Machines is a commercial printer using hot melt extrusion to print pizza, hamburgers and cookies with several ingredients (Sun, Peng, et al. 2015). Burritobot can prepare customized burritos extruding beans paste and a choice of Mexican sauces (Pallottino et al. 2016a). The new XYZprinting solution can print personalized cookies and the TillYouStop project by Mischer'traxler customizes cakes decoration (D. Sher 2015). Ink Jet printing presents solutions for people with mastication problems in the PERFORMANCE project by Biozoon Food Innovation, where the usage of flours derived from insects (i.e. alternative ingredients) allows to prepare cookies and other kind of meals (D. Sher 2015). One of the first and oldest AFM application is CandyFab, that in 2006 has been starting producing candies through sintered sugar with added flavours. Dovetailedcan print fruit using the Photopolimerization technology (D. Sher 2015). Experiments combining AM technology and microencapsulation (Sun, Peng, et al. 2015) of proteins, vitamins etc. are the next step in content customization toward a personalized nutrition, in particular for special population segments like children, pregnant women, aging population, sick persons (Moskowitz, Howard, et al. 2009). Even defence and space sectors and flight industry are starting experimenting customized printed meals on remote sites for their personnel working under special and stressful conditions (D. Sher 2015).

Shape customization introduces new complex geometrical shapes and textures, either not possible or very difficult and expensive to obtain with traditional methods. Chocolate is the main used ingredient by Cornucopia's Digital Chocolatier prototype and commercial: Choc Edge's ChocCreator, 3DSystem's ChefJet, EssentialDynamics' Imagine3Dprinter (Sun, Peng, et al. 2015). Barilla has presented a 3D printer, realized by TNO, able to print special formats of pasta (Pallottino et al. 2016a). It prints with a very low rate (4 pieces every 2 minutes), and then it is not suitable for the industrial production lines, but it can find application at home or, in future, in some restaurants or pasta maker shops. Anyway, an environmental studio is needed about the energetic consumption of the system to produce the right quantity of product in the right time. Other commercial examples of shape customizations are: MakerBot's Replicator for cookies, DeGrood Innovations' FoodJet for cookies and bench-top food paste shaping, 3DSystems' CocoJet consumers printer and the RIG's FoodForm 3D robot able to print ice cream of various shapes (Sun, Peng, et al. 2015) (3DSystems 2014) (D. Sher 2015).

Typical industrial AM applications, such as Rapid Prototyping (RP) and Rapid Tooling (RT) (Sisca, Angioletti, et al. n.d.) can also be applied to food sector.

AFM as RT is used primarily for mould printing to serve the production line for speeding up mass customization process. Moulds have to be made of food-safe Class VI FDA-approved material and reproduce complex and personalized shapes, like scanned customers' faces and bodies. This enable rapid customization industrial production at low cost, since moulds can also be reused for next orders (Halmes & Pierreu n.d.). RP applications of AFM may produce edible prototypes to be used as visual aids of new food products and receipts for design and pre-production studies. They can be used for presentation and taste trials for customers and buyers in marketing meeting and commercial fairs, or directly destined to consumers in public events. Moreover, not just food products, but also industrial ones can be rapid prototyped with edible and organic ingredients, as chocolate, instead of materials with higher environmental footprint and difficult to recycle. The edible prototypes can either be presented to clients and eaten when their functional role ends or they can be given to users as gift that they can taste, instead of throwing away after the event (Godoi et al. 2016b) . This reduces waste of inorganic materials and even advanced samples can be consumed, eventually by animals, if not suitable for humans anymore or re-processed and re-used for new prototypes. AM prototyping can use both edible fresh ingredients and food scraps as source ingredients for the AM process. This can also enable biological re-flow thus accelerating the creation of circular systems (circular economy) (C.M. Angioletti, F.G. Sisca, 2016) .

A futuristic application of AFM is bio-fabrication of meat. The process studied by researchers grows animal staminal cells, then printed to form meat products (D. Sher 2015). Theoretically, such an application of AFM would lead to a decrease of the impacts of human activities on environment as intensive livestock have huge footprints on a long run (D. Sher 2015). However, it is still one of the vanguard researches in AFM up today.

6. Impacts, advantages and limitations of AFM

3D printed food can be used in support of three different market levels (Lipton et al. 2015): home-made food, industrial small scale production, like shops, restaurants, bakeries, and industrial scale production.

Whatever the applications are, the advantages and limitations of AFM and their impacts on the end-use properties of the materials need to be highlighted in order to profitably exploit its full potential (Godoi et al. 2016b). The most impactful advantage of AFM is the capability to allow customized food design, both in shape and nutritional content (Watzke, H., & German 2010). AFM can enable a precise control of people's diet, and ensure to meet needs and preferences of individuals affected by intolerances (e.g. gluten free diet). In this case, even food ingredients characterized by well-known material properties must be tailored to specific formulations according to the fabrication processes (Sun, Peng, et al. 2015).

Another advantage of AFM would be in obtaining simplified, agile and closer to the market supply chains. In fact, AFM printers would facilitate the implementation of a build-to-order strategy with low overriding costs and production facilities located closer to the final customer. This would result in customized food products brought to consumers within a shorter time, together with an acceptable price as fewer resources have been used (Sun, Peng, et al. 2015). Moreover, making synergies with other smart technologies (e.g. industrial IoT, big data) industries might build ecologic systems based on AFM printers sat in manufacturing networks which can order new ingredients, prepare food on demand and even collaborate with doctors to develop healthier diets (Sun, Peng, et al. 2015). Another big opportunity brought by AFM is the possibility to use alternative material such as fungi and algae, rich in nutritional values, but not workable with traditional techniques. AFM may allow to make combinations of materials and process new, more nutrient and eco-friendly materials. Food printers introduce artistic capabilities to fine dining, and extend mass-customization capabilities to industrial culinary sector (Sun, Peng, et al. 2015).

On the other hand, different limitations have to be overcome in order to foster the use of AM in food.

First of all, AFM applications are still at a low maturity level as they have limited internal structures or monotonous textures (Sun, Peng, et al. 2015). The number of applications and the degree of freedom in the use seem to be still limited for the end user (Pallottino et al. 2016a). Moreover, certain AMT have specific limitations too, for example the choice of food grade binder can restrict the use of 3D printing (3DP) (Godoi et al. 2016b).

Furthermore, most of food processing technologies associated with chemical and physical changes may not match requirements of 3D printing technologies. This applies to composition (ingredients and their interactions),

structure, texture, and taste. Ingredients formulation with varied combinations and manipulation conditions can generate various textures in products, which may go beyond a manageable level.
Eventually, conventional food processing technologies are unlikely to be employed as-is and the whole process should be reformulated, for example pre-conducting some processes (e.g. gluten formation and leavening) and replacing remaining processes (e.g. shaping and baking). (Sun, Peng, et al. 2015)
Another AFM limitation is due to the fact that most AMT adapted for AFM are developed for mass production, thus food creativity and user control on shapes, structures and flavours are usually sacrificed (3DSystems 2014) (Sun, Peng, et al. 2015).
Furthermore, there is the feeling thata AMT are likely to reduce economic impacts on the whole lifecycle of products, but it has to be investigated if sectorial specific features bias these expectations. The lack of tools in addressing that topic is evident, thus the need to further research effort.

Table 3 presents a SWOT synthesis of strengths, weaknesses, opportunities and threats of AFM in terms of applications, materials and technologies.

Table 3: SWOT analysis of AFM

Strengths	Weaknesses
Customized food design	Primitive textures and internal structures
Customized nutritional content	Specific technological limitations
Simplified food supply chains	AMT and cooking processes re-thought for AFM
Opportunities	**Threats**
Fulfilment needs of special sectors (e.g. space, defence)	
More eco-friendly manufacturing systems (e.g. bio-material for RT and RP)	Conflict among alimentary function and other functions
More agile and eco-friendly supply chains	Lack of cost assessment tools to support investment analysis and comparison with traditional processes
New usable ingredients (e.g. algae)	

7. Conclusion

As shown in this work, AFM has the potentiality to impact on both consumer and industrial contexts in terms of food customization, innovative receipts and products, new business models and solutions for the manufactures of food and related processing machines. Even new markets can be opened through the development and diffusion of AFM, for instance in agriculture where part of farm production could be converted to be used for AFM supply chain, as already happen in the energy industry for bio-fuel production. Moreover, some basic food ingredients currently used just for animal breeding can be partially converted for the ad hoc production of doughs for AFM systems. Technical, environmental (footprint) and economical studies need to be carried out for this purpose, considering the peculiarities of products, like animal breeding flours, used for AM mixtures and doughs with specific characteristics needed for the extrusion process and the product stability. On the industry side, a further investigation about the potentialities of rapid tooling and rapid prototyping is needed and this can be another further development of the authors studies.
Only through a holistic approach AFM can meet customers' needs and develop its potential benefit to change people lifestyle and the whole manufacturing systems, towards a more customer oriented and environmental friendly approach and the circular economy paradigm. In this context, we thought to propose some future development of this research, considering the qualitative approaches of this paper. It could be useful to study this topic in a quantitative way, trying to estimate the achievable benefits that can be generated from AM application, focusing on the topic of the production costs in order to understand the differences with to traditional techniques. Another important development of how the AM technologies could support the food sector is inherent to the New Product Development process (NPD). Indeed, given the characteristics of the sector (characterized by a high volatility of the demand and by the necessity of flexibility in meeting the customers' needs and the stringent regulations) the use of such technologies in the NPD process could help to face the various challenges previously identified and to meet the need of the food companies to innovate in order to remain competitive in the market.

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