State of the Art of Sustainability in 3D Food Printing

Gulsen Bedia Otcu
Department of Management, Economics and Industrial Engineering
Politecnico di Milano
Milan, Italy
gulsenbedia.otcu@mail.polimi.it

Lucia Ramundo
Department of Management, Economics and Industrial Engineering
Politecnico di Milano
Milan, Italy
lucia.ramundo@polimi.it

Sergio Terzi
Department of Management, Economics and Industrial Engineering
Politecnico di Milano
Milan, Italy
sergio.terzi@polimi.it

***Abstract*— 3D Printing or Additive Manufacturing (AM) has become an emerging trend in global production area with a wide range of application fields. The increasing number of the concepts indicates the opportunity to address the needs and challenges of AM in both food industry and global scale. The technological, resource and industrial aspects of 3D Food Printing have the potentialities to enable to 'print' highly customized food, not just about the shape, but also about the structure, texture, flavor, taste, nutritional value, new edible alternatives and specific formulations for different choices, where the individual meals become possible. Anyway, the increasing importance of global concerns push towards the consideration if the value of the printed meal and 3D Printing itself can be sustainable and how. Whereas several studies claim to address the sustainability of 3Dfood printing, it is not clear yet what is the state of the art of 3D Food Printing within the sustainability intersection of economic, environmental and social pillars. Starting from the presentation of the available current approaches and practices, the paper provides a holistic outlook of the topic, shows the parameters that impact the sustainability of the technology and propose the improvements to be applied for completing the sustainability view and to achieve the 3D food printing full potential.**

Keywords—3D Food Printing, Sustainability, Additive Food Manufacturing, Food sector, 3D Printing, Additive Manufacturing

I. Introduction

Additive Manufacturing (AM) is one of the most sensational and emerging technologies which distinguishes from the commonly known manufacturing techniques. 3D Printing (3DP) which is the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology [1], is a derived process under the '*umbrella*' of AM. As the terminology indicates, 3D Food Printing (3DFP) technology is characterized by a layer by layer material deposition mode based directly from a pre-designed CAD file [2], where the processed material is food.

By the inspire of 3D Food Printing concept, the meaning of the food has been one step away from the change. This new way of application of 3D food printing is able to shape how the food is processed, formulated, prepared, cooked, served, eaten and even digested [3].

3D Food Printing brings together the diverse fields of applications that are constantly growing such as medicine, gastronomy, engineering, manufacturing, art and education [4]. This multi-disciplinary base of the technology is pertaining the potential which enables to 'print' foods highly customized, where the individual meals become possible.

Considering the shifting demand from standardized products to tailor made ones, 3D printing allows for mass-customization of consumer goods, offers the potential for creating such lasting objects of desire, pleasure, and attachment [5] as 3D printing, extends people's horizons with unlimited freedom to design by creating more responsible products while maximizing economic and social impacts and minimize any harmful effects on environment.

In this regard, the discussions about the sustainability of 3D Food Printing concept arises since the beginning of its market adoption. The willingness to use it and the resulting benefits are connected to each other, so that the potential of 3D Food Printing can be fully extracted, when the technology is placed on a sustainable ground.

3D printing, merged with the food evolution to become 3D food printing, demonstrates an exponential growth in both literature and practice in last few years, while opening a new niche in the market. The opportunity to produce highly complex and high value products in small-scale creates demand towards the technology by stimulating the consumer preferences. The notion of customization is the key for food printing which is corresponding to the personalized not just from the shape, structure, but also texture, flavor, taste, nutritional value, new edible alternatives and specific formulation for different choices. Besides, the participatory environment and demand characteristics influence, the trend of 3DFP estimated to reach 425 Million USD worth market size by 2025 [6].

Since 3DFP technology is a brand-new niche in the food industry, the main research question for researchers and practitioners is: how this technology can be sustainable, in order to create a replicable business in the sector? To carry 3DFP closer to the mainstream level, there is a need to understand what kind of tools are defined for assessing and ensuring the sustainability of the system of the business of the companies adopting 3D food printers, overall in small-scale production? The paper addresses 3DFP from the sustainability perspective while assessing the current state of the art of the technology. The findings of the paper have the purpose to deeply assess the perspectives of 3DFP sustainability, in order to understand not only the current status of sustainability studies for 3DFP, but also to prepare the basis for a sustainability framework and model and future research steps in the topic.

The paper is organized within five sections, including this introduction. Section 2 define the context of sustainability considered for the state of the art study of the 3DFP and background studies. Section 3 presents the methodological perspective of the paper. Section 4 provides general review of 3D food printing. The literature review and the summarized results are presented and discussed, enlighting the sustainability approach in 3DFP concept. Section 5 shows the conclusion and future research directions about the topic.

II. EXISTING THEORIES & PREVIOUS WORK

The research is based on the wide accepted definition of sustainability in the Brundtland report for the WCED in 1987, where Sustainability is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7] and it includes social equity, environmental protection and economic prosperity aspects [8].

Dabbene, Ramundo and Terzi presented in 2017 an economic model for the evaluation of 3D food printing [16], where they identified three main aspects to be considered from the economic perspective. First of all, the 3DFP technology is still in its early development and adoption comparing to the general AM solutions and then a continuous assessment of its commercial potential needs to be evaluated. Second, the food ingredients and how they can be pre-processed in terms of raw material and post-processed for the meal presentation and consumption can open new markets and can also have a deep social acceptance and impact on the 3DFP spread. Third, the new skills needed by the food sector to exploit the full potentialities of 3DFP. Moreover, they envisaged the need of a future research about 3DFP sustainability, as main gap in literature.

III. METHODOLOGY

The study originates from the evolution of people lives in the era of emerging technologies and digitalization. From micro to macro level, the new concepts and unexplored areas of food industry are offering a space to be deeper examined by bringing multi disciplines together. Since 3DFP is a relatively new area, some studies are still needed to demonstrate the benefits the technology is capable to offer, and the challenges of food industry is able to overcome, and to identify the conditions needed to take 3DFP adoption to higher levels. As explained in section two, having a understanding of the technology in terms of sustainability is valuable to ground future studies and approaches demonstrating that the integration of economic, environmental and social aspects of 3DFP can enable its full potential.

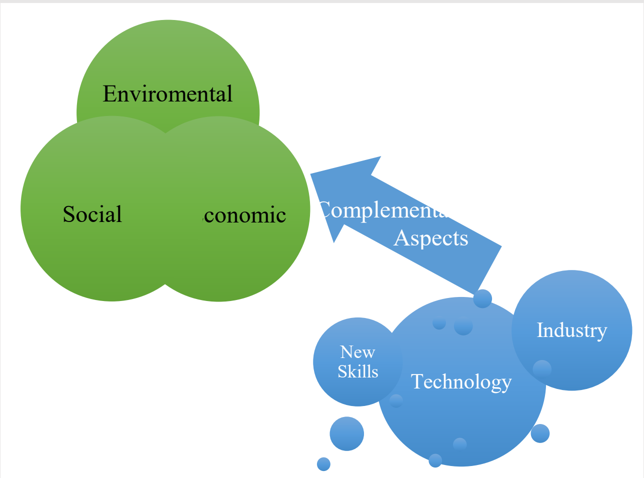

Fig. 1. Components of sustainability for 3D food printing - main dimensions of sustainability (green) and complementary aspects (blue)

Starting from the Dabbene economic model for the evaluation of 3D food printing [16], the authors assess in this research the status of, overall, the environmental and social dimensions and the consolidated scientific methodologies used for their study to prepare the ground for the future development of a sustainability model of 3DFP. To create a value added and a win-win-win condition for each side of sustainability, this study includes into the balanced concept of the three dimensions the complementary aspects of the technology, new skills and Industry. See “Fig.1”.
The research approach evolves from the more general technological study, through the industrial applications and towards the sustainability concept, considering the system connectivity and complexity, where there are trade-offs, synergies and multi-directional impact on or within each dimension. See “Fig. 2”.

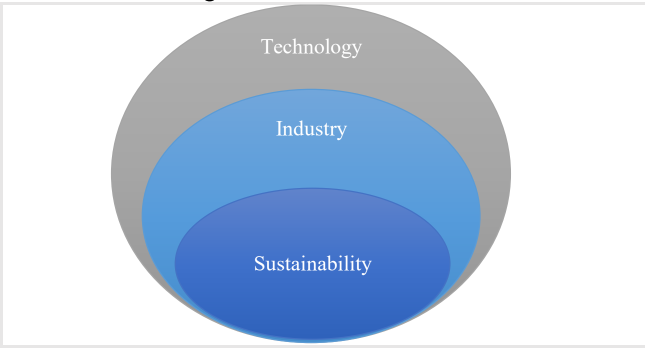

Fig. 2. Elements of complementary aspects - Relationship of sustainability with other aspects

In years, the opportunities and envisaged benefits have created more ambitious researches to mitigate the limitations and enhance the implication capacity of the AM, anyway a structured sustainability study of 3DFP is not available in literature yet.

The research method adopted by the authors is based on the scientific literature review, the analysis of conference proceedings, market researches and reports of international organizations to build a value oriented structure on the technological and functional dimensions of the 3DFP within the sustainability concept. The research has been carried out with a qualitative and quantitative approach including the empirical results of the practices in the literature and articles.

The scientific search engines (e.g. Google Scholar, Sage, Science Direct, Springer, Emerald, Scopus, Taylor & Francis Online, and Wiley Online Libraries) have been searched for a scientific literature background. The presentations of the 3D food printing 2018 conference in Venlo (The Netherlands) – (“https://agrifoodinnovationevent.com/2018-edition/”) and the videos of Seeds&Chips - Food Innovation Summit 2018 – Milan (Italy) – (“https://www.youtube.com/channel /UCcLhMlKSTjDdCErSy29JDZw/video”) have been also studied and analyzed. The web has been surfed as well, for collecting the news linked to the market and from international public and private institutions, for a comprehensive overview of the topic. By considering all the results, a structured literature review has been performed, and the main results are summarized in section four.

The literature review approach of this research is of an iterative nature and starts from 3D Printing in general, its types, applications and characteristics, in order to widen the knowledge about the technological background. This level of the search includes the synonym keywords for 3D Printing as additive manufacturing, direct digital manufacturing, rapid prototyping. The state-of-the-art is then focused on 3DFP studies and finally on the sustainability dimensions. The working principles, challenges and advantages have been also identified to strengthen the basis and to explore an open space for building relation with further steps. Multiple combination of keywords has been used, such as: 3D food printing gastronomy, 3D food printing prosumer, personal fabrication, 3D food printing sustainability/ sustainable, 3D food printing environment/ 3D food printing environmental impact, 3D food printing social/ 3D food printing social impact, 3D food printing economy and so on. The keywords have been defined iteratively according to the previous search results. The papers, for instance, where sustainability aspect is mentioned within, provide qualitative and partial basis of the concept. Therefore, the research has been extended to more generic 3D Printing and AM sustainability studies to find the availability of the approaches or methods applied in the sector and then to understand if and how they can be applied to the 3DFP context.

IV. Findings about the State of the Art for 3D Food Printing Sustainability and Food Industry

Recently, 3DFP, which has an exponentially increasing popularity, adaptation experiments and interfaces, has started to become attractive for deployment in the market as shown in “Fig. 3”.

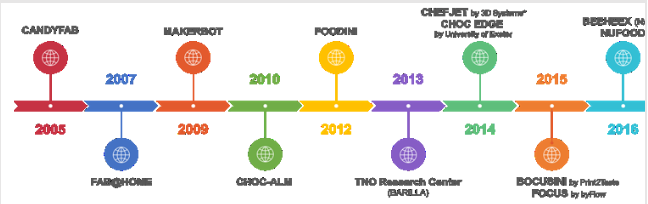

Fig. 3. Timeline of development of 3D Food Printers

In this regard, the blended value of economic, environmental and social aspects is expected to create an exponential momentum to a fast-moving world within a sustainable understanding. The range of practices induced at the lab level, spread from R&D activities to restaurants and confectionary shops, even for space missions and military based [9] on the wide range of food printability, which consolidates the sustainability array.

A. *Current status of 3D food printing research*

In the literature review, 278 sources have been read and assessed, in relation to 3DFP technology and to 3D printing and sustainability. After a refining process, 214 sources have been considered, which includes 152 scientific papers, overall about the technological developments. When the time frame is narrowed, the number of sources are 147 between 2010 and up-to-date. Finally, the 3DFP sources have been concluded in 77 as the types are shown in “Fig. 4”. Due to space constraints and repetitive content, only 53 references are included in this state of the art review paper.

Due to the novelty of food printing concept, the possible information has been acquired from the accepted guidelines, the reports of both supranational, international organizations, and global consultancy companies. For keeping the up-to-date characteristics of the subject, the online sources and latest developments are also referred including the web-sites of 3D food printer producers that provides verified information, where it is necessary.

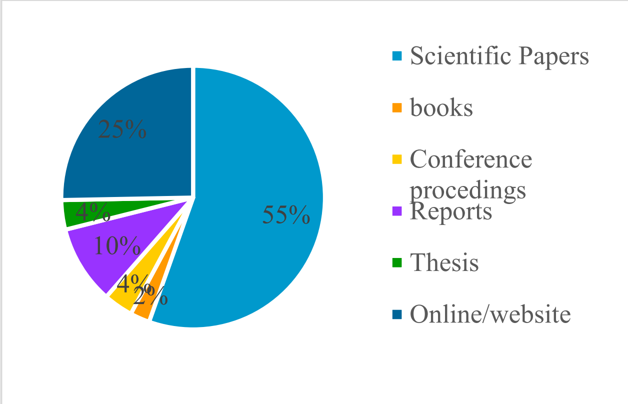

Fig. 4. Types of referenced sources about 3DFP

After a clusterization based on the types of the sources, the reviewed academic studies have been assessed based on the publishing years. The time interval has been considered from 2010 to 2018 that indicates the trend for scientific researches increasing by years as shown in “Fig. 5”. 2018 papers publication was not finalized at the time of this study.

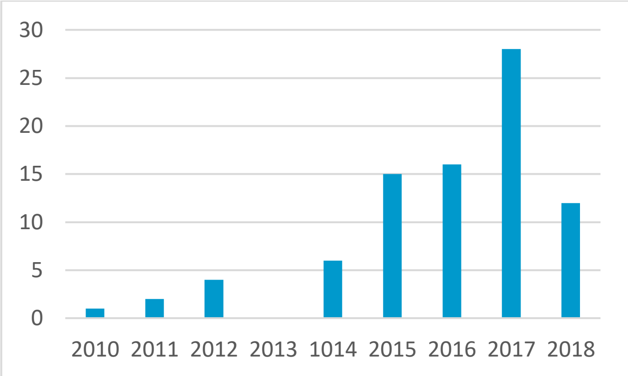

Fig. 5. 3D food printing academic studies by years

According to Dabbene et Al. [16] the small batch production will be the initial sector of adoption. To verify the consistency and accuracy of the convenience of small-scale applications, the literature review has been focalized to the production volumes.

Lipson and Kurman [10] states that the number of small numbers of unique, constantly changing high margin products, 3D printed production represents an evolutionary leap forward. Kohtala [11] describes that SLS allows small batches at the same cost per piece and customization of each piece or batch to an extent that industrial manufacturing can never reach. When compared to mass production processes, digital manufacturing has the potential to reduce material, waste and energy, at least for small batches and may mitigate negative impacts connected to supply chains. Despiesse and Ford [12] [13] states the small batch implications of the technology and presents that the additive manufacturing enables a shift from traditional mass production methods and economies of scale to small batch production of customized goods at more affordable prices while Attran [14] highlights that small batches can be produced cost-efficiently by using additive manufacturing.

Kerbrat and colleagues [15] states that the developed LCA methodology allows to analyze and improve the process knowledge, especially for manufacturing prototypes or small batch sizes.

Specifically, for 3DFP, the customized fabrication in small batch for food has been analyzed by Sun and colleagues [16], Mani and colleagues [17], and Dabbene and colleagues [18] as the overall results are shown in "Fig. 7".

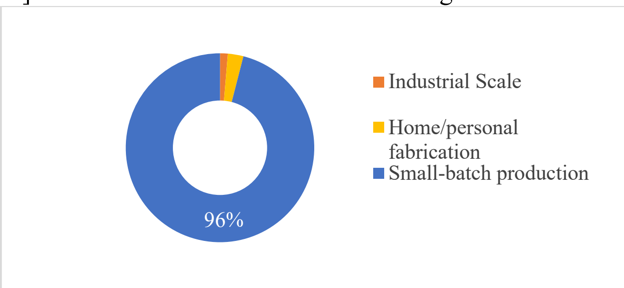

Fig. 6. Production volume of 3D printing for food and non-food materials

The search has been executed for 3DFP and synonym notions with the keywords of environment/environmental to find out the relevant background to gather knowledge as qualitative, empirical or case studies in literature. As "Fig. 8" demonstrates, there is no available study on 3DFP directly referring to environmental dimension. For this reason, a wider search about 3D printing has been done, resulting in 15 studies.

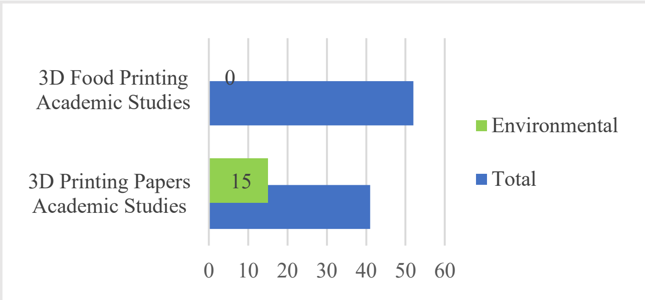

Fig. 7. The studies of 3D printing for food and non-food materials that has direct environmental scope compared to total number of studies

The search has been extended for 3DFP and synonym notions with the keywords of social/societal/society to find out the social aspects of the concept to gather the background about the researches in both qualitative and quantitative basis including case studies. This search extended to the 3D Printing and synonym terms in order to both understand the approaches and evaluate the results whether the findings are adaptable for the food applications. While directly social-oriented papers take a small portion in both food printing and additive manufacturing literature, generally the social are described in sub-sections or in the extent of health or nutrition benefits by indicating a relatively indirect relation as shown in "Fig. 9".

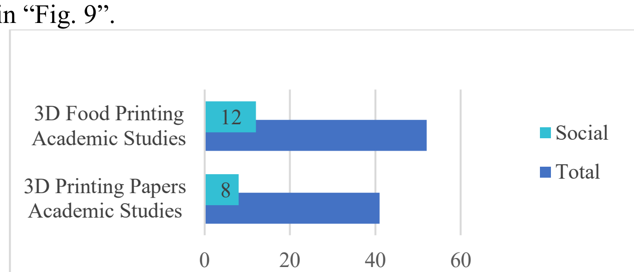

Fig. 8. The studies of 3D printing for food and non-food materials that has social scope (indirect-partial) compared to total number of studies

For the industrial scope, since the trends and evolution in food industry are essential to understand and reflect clearly in the study, another search process provides is needed to have a profound insight about envisaged sector landscape, changing drivers in terms of customer, supplier and business model shifts. Therefore, future of food, molecular gastronomy which deals with culinary transformations and the sensory phenomena associated with eating [19] and digital gastronomy which describes how digital fabrication technologies can be integrated into the kitchen and influence the eating experiences and the process of cooking by playing a new role in food's preparation, culture, economy, physics and chemistry [20] become the subject for this part of the search as shown in "Fig. 10".

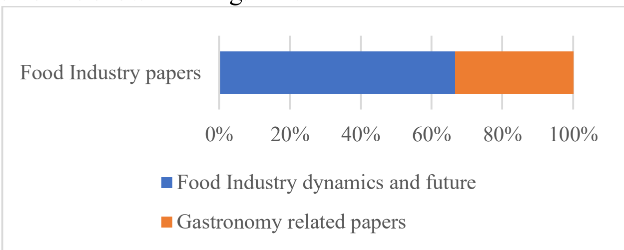

Fig. 9. Distribution of food industry papers between industry dynamics/future and gastronomy

To examine social, environmental and economic dimension of 3DFP, the review of the literature has been performed on the direction of having a deep look to the studies for these three main dimensions as well as sustainability and technological perspective. While there are some studies and reports about these aspects, the vast majority of the papers has been related to 3D Printing in general, industrial applications; metals, plastics, new materials at most as some of them are also referenced [21], [22], [23], [24], [25] by obtaining the information for being adapted to the extent of food printing.

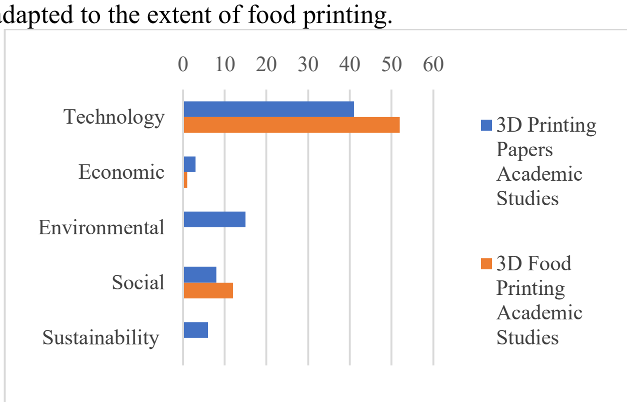

Fig. 10. The categorization of papers on 3D printing for food and non-food

As the categorization of the academic and scientific references indicate in "Fig. 11", the technology aspect is the major topic for 3DFP where the reason is to be an emerging technology. This category represents the working or printing principles [26], [27], recipe consolidation [28], [29], [30] and use scenarios [31] in both qualitative and empirical way. The economic category represents the industrial and economic value of the end-products while environmental and social shows the papers that contain respectively environmental and social benefits of the technology. The papers where sustainability aspect is mentioned, provide qualitative and partial basis of the concept. Therefore, the research has been extended for finding the availability of the approaches or methods to have a whole and comprehensive sustainability structure for 3DFP.

978-1-7281-3401-7/18/$31.00 ©2019 IEEE

B. *Current approaches and methods for 3D food printing sustainability*

The above insights and knowledge has driven the literature review to the sustainability concept. This top-down approach then enable to understand which methodologies and roadmap can be applied while assessing the sustainability dimensions of 3D food printing.

In this extent, sustainability and 3DFP and synonym keywords additive manufacturing, direct digital manufacturing, rapid prototyping, has been searched. However, sustainability either has taken place as a section or sub-section in the studies by providing general idea about the concept in 3DFP studies [32] or approached in the additive manufacturing/3D printing concepts [33]. The main issue is the most sustainability descriptions indicate only either one or two dimensions (environmental, socio-environmental, socio-economic) rather than three integrated pillars.

As there are no detected sustainability studies for 3DFP, the limited number of studies about sustainability in 3D printing or additive manufacturing, have been assessed for non-food applications [34], [11] in a broader search. The existing methodologies and approaches of the researchers have been summarized with the evaluations in the 3DFP extent and are provided as follow.

The value stream mapping which includes set of metrics to evaluate not only the economic performance as well as environmental and societal sustainability performance of a manufacturing line [35] with the metrics to assess process water consumption, raw material usage, energy consumption, potential hazards concerning the work environment, and the physical work done by the employees. This study includes three dimensions of sustainability and the visualization of the production processes, yet the knowledge on lean manufacturing of food printer adopters needs to be considered where the market maturity is at early stages to apply continuous improvement practices in 3DFP field, to interpret the impact.

The research activities on economic sustainability of 3D printed chocolate business by setting up a computer aided simulation model [36] as two-sided case studies are based on the scenarios for business model and supply chain in order to evaluate the adoption of the technology. The simulation and scenario based assessment has been clearly reflecting market application of 3DFP, yet the environmental, social or other dimensions need to be included to reach a complete concept beside a need for virtual simulation competences.

One methodology in the literature is the Delphi method [37] as the researchers used Delphi method which is an interactive multi-stage forecasting method by involving complex opinion groups and develop consensus ultimately, to predict the economic and societal implications of 3D printing for 2030. Being scenario based and assessment of several dimensions is appealing, yet the requirement for large group of experts may be challenging for wide sustainability concept for a small niche.

A mapping tool which enables to assess environmental implications of additive manufacturing a large set of criteria, not only environmental aspect but social, economic and security related aspects for each additive manufacturing categories [38] as the criteria are classified as benefit or weakness within a time frame from immediate to future implication domains. Another predictive framework is a model uses the Design for Sustainable Additive Manufacturing (DFSAM) approach by focalizing on environmental perspective [39].

Life-Cycle Assessment often lack a sustainability perspective and bring about difficult trade-offs between specificity and depth, on one hand, and comprehension and applicability, on the other [40]. The outcomes indicate the convenience to assess the environmental dimension through Life-Cycle Assessment approach, yet as the researchers highlighted, a broader or extended methodology is needed for economic and social aspects for a complete sustainability framework.

Finally, the value road-mapping framework where the core of this methodology provides the opportunity of additive manufacturing in sustainability terms [41]. Despite the solid basis and visualization of this method, the possible challenges for food printer adopters are a need for new competences and advanced understanding to apply the method in practice.

C. *Sustainability of 3D Food printing discussion*

The review of the methods and case studies results for 3D printing and AM and their integration into the global food challenges, such as food safety, quality and security, are the next research steps to finalize the integration of the three dimension into the 3DFP sustainability context in practice. This creates the ground for building a future 3DFP sustainability model. They are summarized for each dimension as follow.

1) *Environmental Dimension*

The environmental dimension of the fifteen 3DP studies (see "Fig. 8) is emphasized through the benefits of resource efficiency in terms of energy, raw material and water. Considering the technological challenges, printing speed is both an effecting parameter and effected by the printing movement axes and the amount of food deposited [42], therefore it affects the energy consumption and final product quality.

For the customized and complex products, the requirement of resources, less carbon footprint and produced waste are considerably eco-friendly compared to the conventional methods [36]. This can be translated in relation to the 3DFP in reduced production resources and food waste. Moreover, less food waste can trigger resource efficiency, such as less soil requirement and less carbon footprint. Especially, small batch production increases the focus on the process, which provides a better utilization of materials, which is a consolidating factor for food availability and quality of environment [16].

The AM along with a new lean yet agile business models will stimulate the local manufacturing and use of local materials and thus revive local economy and productivity [21]. In the light of value chain reconfigurations, the shift of supply chains to become shorter and responsive, holds the greatest benefit on environment [31], [44]. Since the carbon emissions are the one of the most determining factor in the production, also 3DFP holds a clear potential to reduce carbon footprint of the products along their life-cycle.

The raw material choice has an influence on the sustainability of the AM [43], in fact 3D printers production processes (i.e. for spare part production, plastic objects, etc.), and extruding plastic filaments, melting and printing processes cause Volatile Organic Compounds (VOC) and Particulate Matter (PM) which are potentially harmful for health and environment [44]. 3DFP causes no pollutant emissions during the printing stage. Therefore, printing the food eliminates the risks of harmful impact.

3DFP also overlaps with the healthy life-styles and diets, starting from the field or farm stage, the raw material of food has been driven to be more organic and usually plant-based which has a lower carbon footprint. Jet-Eat, for instance, produces plant-based meat steaks, with very low carbon and water footprint, comparing to animal meat. [45] The alternative foods are also critical to overcome challenges of resource dependency as 3DFP enables to produce edible insect meals as novel source of proteins [46] by adding new low-carbon edibles into the menus.

While the quality of food products depends more on the fabrication process rather than operator skills [16], the efficiency of the printing process is strongly influenced by the operator's level of professionalism [25]. Therefore, to reduce environmental impact by avoiding the repetitive, redundant or inefficient activities for material and energy flow in both CAD and printing processes, the operator skills are critical. As stated above 3DFP adoption can eliminate some supply chain activities and sub-activities. While assessing the impact that is influenced by the shortened supply chain, the life cycle thinking becomes, from methodological point of view, a facilitator approach to avoid the impact as a shifting burden along the life-cycle.

2) Social Dimension

The social dimension of 3DFP is highlighted through the potential benefits of personalization or flexibility of printing food [47], quality of food and production aspects. The content of the social aspect corresponds to the acceptance and benefits for each group of stakeholders in the 3D food printer adopting business and having small-scale production. [48] states that, beside the first impression of consumers towards printed food, well-designed communication has the potential to positively shape consumer attitudes towards 3D printed food by giving information about the technology and application scenarios.

3DFP offers the possibility to introduce alternative foods which varies from the plant-based meat [45] to the algae and insect meals, reach of proteins, [46] in desirable shapes and tastes, increasing food security options. Despite the efficiency, nutritional capacity and sustainability of these ingredients, they are commonly perceived as 'ugly food' or creating resistance to eat [46], [47]. 3D food printers turn these substitutes into appealing options by means of taste, texture and shape which can also break the biases towards them.

Currently, the wide spectrum of the printable materials from fruits, potatoes to dough, dairy products, enables to enhance the menu of printable foods [2], [7], [18], [24], [25], [29], [34], [42], [46], [51]. The major social benefit of 3DFP adoption is observed as the customization of food [3], [4]. The personalized printed food offers a great value for elderly, athletes, children, expectant mothers, children or any specific group who has peculiar needs and different nutritional or healthy ingredient desires by customizing the micro-, macro-nutrients and the other food constituents in required amounts and portions [3], [4]. The creative shapes and textures are the other type of customization as the variety of ingredients, constituents of food take a shape dripping off from the imagination [24]. Beside the appealing shapes and structures of food that comes with the perception of value, it generates an experience for both the producers and consumers [47], [48].

The improvement on the social aspect is hand in hand with new technological advancements on 3DFP area and digitalization trends. The authors consider the usage of pre-filled cartridges [16] can provide a way of portion control helping to combat obesity. Considering the foreseen resource scarcity and malnutrition problems, the capability to print alternative edibles, ingredient variety, and to allow preparation of balanced diet and enriched nutrition content meals make 3DFP a valuable solution towards food security with personalized quality. Food safety can be provided through the process without human intervention, long shelf-life cartridges and instant preparation of meals, even in space [7] and remote areas [52]. The researchers also highlight the sanitization problems of each part of 3D printer in contact with food to be tackled for obvious safety reasons for its application in restaurants and at industrial scale [51]. The advancements on these fields will provide a clear advantage to go beyond the state of the art while offering a more sustainable frame for market uptake.

3) Economic Dimension

The food waste reduction and process efficiency are key features of 3DFP to decrease the burden of both societal, environmental, ethical and industrial, health care expenses including economic contribution. Restaurants and food manufacturers can create diversified food products from a small number of ingredients which has added value on customer perception [47], [48], which means the products can provide high economic return in small volume [16].

3DFP can shorten the supply chain, while making the supply and demand much closer in terms of distance or time compared to the traditional production. The 3DFP activity can either take place in front of the customers or triggered by orders to remote providers [34]. When the manufacturing steps has been moved to the downstream by 3D food printers, the design, manufacturing processes, warehousing, distribution and packaging requirements are entailed to be reduced which can be translated into more efficient businesses and savings.

The possibility to introduce into the market alternative foods, such plant-based meat [45], algae and insect based meals, [46] in desirable shapes and tastes, allow the food industry to create new market opportunities, which tackle the food challenges. Dabbene study [16] also highlighted the prospect cartridges new market, as direct consequence of the 3DFP wide adoption.

4) Industrial, technological and other aspects

One of the food industry challenges is to launch new products which have complex shapes, special textures, flavors and even nutritional content [53] with conventional techniques as it is costly and infeasible at many levels, while 3DFP allows to introduce value-added and customized food easily [16]. From the health point of view, a balanced diet, some clinic diseases and life-style are directly related to the caloric value, nutrition uptake, and personal choices hold new opportunities for the market [3], [4], [8], [18], [30].

Beside human health, well-being, nutritional aspects, the 3D food printers hold opportunities for food industry players in terms of the shelf-life [7], [51]. Based on the printing process, the variables which effect the shelf-life, can be controlled. Therefore, the operational perspective makes 3DFP more appealing to use for food customization [3], [4].

Regarding to the overall supply chain which has very complex structure and components [16] , 3DFP process offers to alter the supply chain dynamics by removing the need for economies of scale and simplifying the up- and downstream activities which means also reduced costs, energy and transportation effort [49], [18], [50], [21] while potentially decreasing time to market and innovation inefficiencies [51].

In 3DFP activities, raw material consumption is controlled, while access to food can be eased for remote [52] and most probably less developed areas.

Food industry will be enhanced by increasing the business opportunities and new job sections for food printing. The new type of jobs which are more engaged with the digitalization, data analysis and integration, creativity, diet and gourmet related positions that operates in the different sections of printed food value chain [16].

Considering health and well-being improvement, and better work conditions, the additive food manufacturing can lead to a decrease in the cost of health care including the rise in personnel health, safety and security [21], which indicates a benefit for the health system.

V. CONCLUSION

The paper demonstrates the state of the art of sustainability for 3DFP has been approached on qualitative, decision-based and with fragmentary basis so far. Scientific literature overall lacks of any study not only about sustainability of 3DFP in all the three environmental, social and economic dimensions, but also in the only environmental one. This is instead widely approached about AM in general and mainly studied through LCA methodology. The social aspects instead are more addressed in the 3DFP literature, since strictly linked with consumer acceptance of printed food and alternatives ingredients (insects, algae) meals, and with global challenges, such as food waste and food security. The economic perspective is modestly addressed through simple application cases and promissory themes. Only one economic model for the evaluation of 3DFP is currently available Starting from those results, the authors have discussed the integration of the different components of sustainability into the 3DFP, presenting a more integrated and holistic approach. Even if still at qualitative level, the study has the potential to understand and improve current practices while addressing the market and global challenges.

Among all the potential benefits and opportunities, 3D Printing in food sector is a small niche, where its unique position and examinations for adaption is still going on. The scientific researches, the investment of incumbent companies on R&D and applications of the technology are on development stage and expected to be jump up in near future.

The dimensions of 3DFP, under the sustainability umbrella, demonstrate obvious a need for a set of components to formulate the relationships within a framework. While eliminating the trade-offs between dimensions and system components, the synergies to achieve are critical to illustrate sustainable outcomes. In addition to that, a unified framework is valuable for increasing the applicability and for unlocking the opportunity to discover the sustainability intersection.

The results have revealed that 3DFP adoption for small-scale production has the potential to influence on energy use, resource efficiency, carbon footprint, human health, nutrition/food customization and food quality. Also, the new jobs and markets are expected to be triggered by the stakeholders. The most remarkable aspect for sustainability has been found as technology where the advancements on printing speed and integration with devices and digital platforms have been specified to be more promising for the growth of the technology.

A comprehensive and inter-connectedness of the sustainability dimensions in 3DFP are open to the assessments in qualitative, but also quantitatively, in a short to longer term view. A sustainability model is envisaged by the authors as one of the next research steps to be developed.

REFERENCES

[1] ASTM, "ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies," ASTM International, West Conshohocken, 2012.

[2] C. Pinna, L. Ramundo, F. G. Sisca, C. M. Angioletti, M. Taisch, and S. Terzi, “Additive Manufacturing applications within Food industry : an actual overview and future opportunities” in XXI Summer School “Francesco Turco” - Industrial Systems Engineering Additive, 2016.

[3] S. Homer, "3D printing for personalised nutrition," in 3D Food Printing Conference 2018, Venlo, NL, 2018.

[4] I. Dankar, A. Haddarah, F. Omar, F. Sepulcre, M. Pujolà, “3D printing technology: The new era for food customization and elaboration” in Trends in food science & technology, no 75, pp 231-242, 2018.

[5] O. Diegel, S. Singamneni, S. Reay, and A. Withell, “Tools for Sustainable Product Design: Additive Manufacturing,” J. Sustain. Dev., 2014.

[6] MarketsAndMarkets, "3D Food Printing Market worth 425.0 Million USD by 2025," https://www.marketsandmarkets.com/Market-Reports/3d-food-printing-market-267692011.html, India, 2017.

[7] M. L. Terfansky and M. Thangavelu, “3D Printing of Food for Space Missions,” 2013.

[8] H. Lipson, K. Melba, "Fabricated: The New World of 3D Printing", Journal of Chemical Information and Modeling, vol. 53, issue 9 pp. 1689-1699 John Wiley & Sons Inc., 2013.

[9] C. Kohtala, "MAKING SUSTAINABILITY How Fab Labs Address Environmental Issues", Aalto University publication series Doctoral Dissertation, Unigrafia Helsinki, 2016.

[10] S. Ford, M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges", Journal of Cleaner Production, no. 137, pp. 1573-1587, 2016.

[11] M. Despeisse, S. Ford, "The Role of Additive Manufacturing in Improving Resource Efficiency and Sustainability", APMS 2015 International Conference, vol. 3, 2015.

[12] M. Attaran, “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing,” Bus. Horiz., 2017.

[13] O. Kerbrat, "Environmental Impact Assessment Studies in Additive Manufacturing," Handbook of Sustainability in Additive Manufacturing, Environmental Footprints and Eco-design of Products and Processes, 2016.

[14] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Business Horizons ,* 2017.

[15] J. Sun, W. Zhou, L. Yan, D. Huang, L. Lin, "Extrusion-based food printing for digitalized food design and nutrition control," Journal of Food Engineering, no. 220, pp. 1-11, 2017.

[16] L. Dabbene, L. Ramundo, and S. Terzi, “Economic Model for the Evaluation of 3D Food Printing,” in 2018 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2018 - Proceedings, 2018.

[17] S. Rossi-Wilcox, "Molecular Gastronomy: Exploring the Science of Flavor" Arts and Traditions of the Table: Perspectives on Culinary History, The Journal of Popular Culture, vol. 40, issue 5 (2007) pp. 902-903 Published by Wiley-Blackwell 2008.

[18] A. Zoran, M. Coelho, "Cornucopia: The Concept of Digital Gastronomy" Leonardo, vol. 44, issue 5 (2011) pp. 425-432, 2011.

[19] C. Cozmei, F. Caloian, "Emerging Markets Queries in Finance and Business - Additive manufacturing flickering at the beginning of existence" Procedia Economics and Finance, no. 3, p. 457 – 462, 2012.

[20] D. Rejeski, "Research needs and recommendations on environmental implications of additive manufacturing" Additive Manufacturing, no. 19, pp. 21-28, 2018.

[21] A. Drizo, J. Pegna, "Environmental impacts of rapid prototyping: an overview of research to date," Rapid Prototyping Journal, vol. 12, no. 2, p. 64, 2006.

[22] K. Kellens, R. Mertens, D. Paraskevas, W. Dewulf, J. Duflou, "Environmental Impact of Additive Manufacturing Processes: Does AM contribute to a more sustainable way of part manufacturing?", Procedia CIRP , no. 61, p. 582 – 587, 2017.

[23] K. Barros, P. Zwolinski, "Influence of the use/user profile in the LCA of 3d printed products" Procedia CIRP, 26th CIRP Design Conference, no. 50 , p. 318 – 323, 2016.

[24] J. Sun, Z. Peng, L. Yan, J. Fuh, G. Hong, "3D food printing—An innovative way of mass customization in food fabrication" International Journal of Bioprinting, vol. 1, no. 1, p. 27–38.

[25] CandyFab, "DIY 3D Printing in Sugar," [Online]. Available: https://candyfab.org. [Accessed October 2018].

[26] D. Cohen, J. Lipton, M. Cutler,D. Coulter,A. Vesco, H. Lipson, "Hydrocolloid Printing: A Novel Platform for Customized Food Production" in Solid Freeform Fabrication Symposium, TX, USA, 2009.

[27] J. Lipton, M Cutler, F. Nigl,D. Cohen, H. Lipson, "Additive manufacturing for the food industry", Trends in Food Science & Technology, no. 43, pp. 114-123, 2015.

[28] J. Lipton, D. Arnold, F. Nigl, N. Lopez, D. Cohen, N. Norén, H. Lipson, "Multi-Material Food Printing with Complex Internal Structure Suitable for Conventional Post-Processing" in Solid Freeform Fabrication Symposium, Austin TX, USA, 2010.

[29] M. Lanaro,D. Forrestal, S. Scheurer, D. Slinger, S. Liao, S. Powell, M. Woodruff, "3D printing complex chocolate objects: Platform design, optimization and evaluation" Journal of Food Engineering, no. 215, pp. 13-22, 2017.

[30] D. Lupton, "'Download to delicious': Promissory themes and sociotechnical imaginaries in coverage of 3D printed food in online news sources" Futures, no. 93, pp. 44-53, 2017.

[31] M. Gebler, A. Schoot Uiterkamp, C. Visser, "A global sustainability perspective on 3D printing technologies" Energy Policy, vol. 74, p. 158–167, 2014.

[32] S. Yang, T. Talekar,M. Sulthan, Y. Zhao, "A Generic Sustainability Assessment Model towards Consolidated Parts Fabricated by Additive Manufacturing Process" Procedia Manufacturing, vol. 10, pp. 831-844, 2017.

[33] W. Faulkner, W. Templeton, D. Gullett, F. Badurdeen, "Visualizing Sustainability Performance of Manufacturing Systems using Sustainable Value Stream Mapping (Sus-VSM)" in International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey, 2012.

[34] F. Jia, X. Wang,N. Mustafee, L. Hao, "Investigating the feasibility of supply chain-centric business models in 3D chocolate printing: A simulation study" Technological Forecasting & Social Change, no. 102, pp. 202-213, 2016.

[35] R. Jiang, R. Kleer, F. Piller, "Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030" Technological Forecasting & Social Change, no. 117, p. 84–97, 2017.

[36] K. Kellens, M. Baumers, T. Gutowski, W. Flanagan, R. Lifset, J. Duflou, "Environmental Dimensions of Additive Manufacturing Mapping Application Domains and Their Environmental Implications" Journal of Industrial Ecology, vol. 21, pp. 49-68, 2017.

[37] F. Bourhis, O. Kerbrat, L. Dembinski, J. Hascoet, P. Mognol, "Predictive model for environmental assessment in additive manufacturing process" Procedia CIRP 15 (2014) 26 – 31, 2014.

[38] H. Ny, J. MacDonald, G. Broman, R. Yamamoto, K. Robèrt, "Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic" Journal of Industrial Ecology, no. 10, pp. 61-77, 2006.

[39] M. Despeisse, M. Yang, S. Evans, S. Ford, T. Minshall, "Sustainable Value Roadmapping Framework for Additive Manufacturing" Procedia CIRP, no. 61, p. 594 – 599, 2017.

[40] UN WCED, "Report of the World Commission on Environment and Development: Our Common Future (The Brundtland report)" WCED, 1987.

[41] J. Elkington, "Cannibals with forks: The triple bottom line of 21st century business", New Society Publishers (1998) pp. 37-51, 1998.

[42] C. Severini, D. Azzollini, M. Albenzio, A. Derossi, "On printability, quality and nutritional properties of 3D printed cereal based snacks enriched with edible insects" Food Research International , vol. 106, p. 666–676, 2018.

[43] A. Davis, M. Black, Q. Zhang, J. Wong, R. Weber, "Fine particulate and chemical emissions from desktop 3D printers" NIP & Digital Fabrication Conference, no. 1, pp. 121-123, September 2016.

[44] J. Faludi, C. Bayley, S. Bhogal, M. Iribarne, "Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment" Green Manufacturing and Sustainable Manufacturing Partnership , 2014.

[45] B. Eschcar, "Food Printing Manifesto" in 3D Food Printing Conference 2018, Venlo, NL, 2018.

[46] M. Lille, A. Nurmela, E. Nordlund, S. Metsä-Kortelainen,N. Sozer, "Applicability of protein and fiber-rich food materials in extrusion-based 3D printing" Journal of Food Engineering, vol. 220, pp. 20-27, 2018.

[47] T. Brunner, M. Delley, C. Denkel, "Consumers' attitudes and change of attitude toward 3D-printed food" Food Quality and Preference, 2017.

[48] S. Jayaprakash, "Role of Prosumer Driven 3D Food Printing in Innovating Food Value Chains," Aalto University, Espoo, 2017.

[49] S. Tofail, E. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities" Materials Today, vol. 21, no. 1, pp. 22-37, January/February 2018.

[50] D. Sher,X. Tutó, "Review of 3D Food Printing" ELISAVA TEMES DE DISSENY, pp. 105-117, 2015.

[51] C. Severini, A. Derossi, I. Ricci, R. Caporizzi, A. Fiore, "Printing a blend of fruit and vegetables. New advances on critical variables and shelf life of 3D edible objects" Journal of Food Engineering, no. 220, pp. 89-100, 2018.

[52] M. Scerra, "Exploration of 3D food printing and its application for tailored military rations," in 3D Food Printing Conference 2018, Venlo (NL), 2018.

[53] L. Ramundo, S. Terzi, "State of the art of technology in the Food sector value chain towards the IoT" in 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI) (pp. 1-6). Proceedings 2018.