INVESTIGATION OF THE IMPACT OF SUSTAINABILITY ON 3D PRINTING TECHNOLOGIES

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ABSTRACT

3D Printing technologies are becoming pervasive and used both in industry and in informal contexts like domestic self-production and craftsmanship 2.0. A large part of the current studies concerning 3D Printing aims at increasing the performance of processes, materials and devices; however, only few studies approach sustainable issues (i.e. printable eco-materials, distributed networks, etc.). 3D Printing instead could play a crucial role in the transition processes toward the so-called Sustainable Society, if linked with current Design for Sustainability approaches. The paper analyses current literature regarding 3D Printing and Design for Sustainability in order to identify new open research topics and re-think their impact and design roles for future sustainable applications. Specifically, the paper produces evidences linking 3D Printing technologies and Sustainability from the design point of view; it outlines a number of promising open cross-sectorial research topics that aims to anticipate the impacts and the evolution of future Sustainable 3D Printing technologies and new generation of democratic products and services for All.

Key Words: 3D Printing, Design for Sustainability, Sustainable Design Opportunities, New Research Topics.

1. INTRODUCTION

3D Printing is a term used to describe all processes in which materials are joined or solidified under computer controls to create three-dimensional objects having computational-based silhouettes. It was originally born for industrial and commercial-oriented applications but, in last years, the democratization of services and the low prices of devices generated a large number of non-industrial applications (i.e. Fab Labs). However, uncontrolled industrial, commercial and new 'informal' 3D Printing applications – intended as new distributed socio-technical forms of production – might produce unsustainable impacts on the ecosystems. In the perspective of a Sustainable Development defined as 'a development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (UN WCED, 1987), it is important to control this type of innovations to mitigate the anthropic impacts on ecosystems both at micro-and at macro-scale. For this reason, the future development of 3D Printing sector could play an important role in the transition toward the so-called Sustainable Society, becoming more and more a part of new production processes and ways of thinking able to produce radical, distributed and large-scale innovations.

The main problem is that, in last years, sustainable-oriented research on 3D Printing technologies has been mainly implemented through the development of non-connected solutions, vertical approach and mono-disciplinary studies. For example, researches about: eco-efficient materials (i.e. recycled biomaterials); spontaneous forms of services for production (i.e. print-todelivery services, cloud manufacturing); economically efficient services (i.e. 3D Printing for education); architectural solutions for housing emergency and low-tech applications (i.e. DIY 3D printers); etc.

A more systemic approach is therefore needed to connect all existing forms of sustainable-oriented advances – horizontal approach, multidisciplinary research. In the field of Design, new theories and methodologies have been recently developed; they allow to create products and services in a systemic way in terms of social, environmental and economic sustainability. Accordingly, this work is based on the hypothesis that current advances in Design for Sustainability theories (i.e. PSS: Product-Service Systems) (Ceschin and Gaziulusoy, 2016) and SLOC Scenarios (Small-Local-Open-Connected) (Manzini, 2003) can improve the quality of existing 3D Printing related services, generating new opportunities and research challenges. An expansion of current technology-centered 3D Printing approach toward multidisciplinary perspectives can expand its intrinsic potential toward new sustainable scenarios.

2. AIMS

According to the research framework before described, this paper aims to:

- Produce evidences linking 3D Printing technologies and Sustainability, from the design point of view.
- List a number of promising open research topics linking 3D Printing and Design for Sustainability.
- Show the positive impacts of Design for Sustainability in the evolution of 3D Printing technologies toward new generation of democratic products and services 'for All', including new 'Design Opportunities'.

3. METHODOLOGY

This research has been developed using traditional Design Research approach and it is organized in three main phases, and their aims are synthetically described below:

- To study and analyze the literature on emerging sustainable-oriented 3D Printing theories, to know research and technological advances in the field.
- To focus attention on cutting edge Design for Sustainability models, for the implementation of theories.
- To develop a cross-fertilization to generate a design-oriented scenario for Sustainable 3D Printing, which is based on the combination of results achieved in the two research phases.

3.1. 3D Printing's Literature Review

Sustainability-oriented 3D Printing advances follow a vertical approach (i.e. mono-disciplinary research), which is the result of a 'traditional' industrial technology-push culture. In fact, current state of the art of researches and industrial developments, regarding sustainable-oriented 3D Printing, are mainly focused on: innovation in engineering and engineering-related domains (Gebler et al., 2014); low-cost and open-sources 3D Printing technologies services (Canessa et al., 2013); Circular Economy's scenarios – i.e. recycling, low energy grids, etc. (Rifkin, 2012); interdisciplinary applications – i.e. Inclusive Design (Rossi and Barcarolo, 2018); technological improvements of production processes (Liu et al., 2016); development of printable (bio)materials (Jammalamadaka, and Tappa, 2018); new technological components – i.e. semi-finished – including for construction industry. As discussed, the aspects that are most considered are those related to environmental protection (i.e. lowcost processes, mitigation of the impacts on ecosystems, compatibility of materials, etc.). On the other hand, the economic and social sustainability aspects are less considered. A holistic view of 3D Printing is therefore needed in order to evolve the simplistic eco-characteristics of productions, toward integrated approaches that consider all products' life cycle elements, including: material supply, design of solutions, processes simplification, etc.

3.2. Design for Sustainability's Literature Review

It is possible to refer to Design for Sustainability approaches that are 'systemic' in order to obtain a holistic view of 3D Printing. As such, the literature review will be mainly focused on the analysis of the three approaches that are today considered as the most promising ones for current Design for Sustainability Research: (1) Design for Small-Local-Open-Connected Scenarios of wellbeing (SLOC); (2) Design of Product-Service Systems (PSS) and (3) System Design for Sustainability (SDS). SLOC Scenario is a sustainable-oriented design model developed by Ezio Manzini (2010; 2015) where emerging global phenomena are intersected with three main innovations: the green revolution, the spread of networks, the diffusion of creativity. SLOC Scenario directs toward sustainable solutions. In particular, Manzini indicates that such solutions have to refer to the local (e.g. local community) and to the 'small' (in terms of relationships, participation, and democracy).

At the same time, it promotes the solutions' implementation using the framework of the global network society in which the local and the small are both open and connected. PSS is defined as 'a marketable set of products and services capable of jointly fulfilling a user's need' (Goedkoop et al., 1999). According to Mont (2002), PSS consists of a combination of products (eco-designed) and services (designed at different stages of a product's life cycle), closely involving final consumers and actors in the chain. Thanks to this design theory, benefits are produced both for customers and for producers (Ceschin, 2014).

For consumers, we include both buying products and buying services and systems of solutions that minimize the environmental impacts of consumers' needs. For producers, PSS imposes a higher control on full life cycle process (i.e. co-design, closed loop systems). Moreover, there are different benefits in developing a PSS for manufacturing companies (Ceschin and Gaziulusoy, 2016) for example: improving relations with consumers; to increase the product's value, to base a growth strategy on innovation in a mature industry, etc. SDS is defined by Carlo Vezzoli (2010): as 'a design approach for eco-efficiency, equity and social cohesion of systems of products and services, which are able to respond to specific customers' needs planning the interaction of stakeholders and the value's production system'. The SDS's aim is to obtain a product-service system that is sustainable from the environmental, social and economic point of view.

This approach adopts different design tools (i.e. System Map, Polarities Diagram, etc.) and a 'Modular Method for System Design Sustainability' (MSDS), which is based on the interaction between designers and stakeholders to satisfy a customer's needs (Vezzoli, 2010).

3.3. Cross-Fertilization

After the analysis of the literature of both sustainable-oriented 3D Printing and methods concerning Design for Sustainability, in the third research phase a number of new Design Opportunities (DO) – see '4. Results' – have been developed an using a cross-fertilization process, to produce both vertical and, mostly, meaningful horizontal innovations. Accordingly, cross-fertilization has been used as a 'sustainable-oriented scenarios generator'.

4. RESULTS

The research results carried out so far have led to the definition of new Design Opportunities (DO). As shown in the formula below, we can describe new Design Opportunities (DO) as the result of a qualitative analysis developed combining main elements of 3D Printing technologies (3DP) and Design for Sustainability (DfS).

DO = 3DP DfS

In Table 1 four main Design Opportunities (DO), and related sub-themes, are presented as part of an early research framework concerning the 'Sustainable 3D Printing'.

[Table 1] Design Opportunities for 'Sustainable 3D Printing': early results

3D Printing Technological Advances (3DP)	Design for Sustainability Research Approaches (DfS)	Design Opportunities for 'Sustainable 3D Printing' (DO= 3DP .DfS) (S3DP)
1. New materials. 2. 4D/5D solutions. 3. (Recyclable) biopolymers. 4. Lean productions. 5. Green printing. 6. Low energy 3D Printing services 7. Open source. 8. Software R&D. 9. Rapid (raw) Prototyping. 10. Extreme uses. 11. Nano-and Micro-3D Printing	A. SLOC Design. B. Design for SMBs. C. Design for local resources. D. Design and ICTs. E. Inclusive Design (and HCD). F. Design for social innovation. G. Context-based Design. H. Co-Design. I. PSS Design. J. SDS. K. Eco-Design (i.e. LCA and LCD).	• Use of local resources and values for Circular Economies and SMBs, for example: o Creation of renewable, zero impact, eco-and/or biomaterials (i.e. 1, B). o Creation of smart GLocal production networks (i.e. 7+9+20 D+I+J). o (Co-)creation and sharing of tangible and intangible resources (i.e. 7 H). o Development of B2B services for SMBs and SMEs (i.e. 4+6 G+S). o New business models for social inclusion and innovation (i.e. 3+5 E+F). • Extension of local values in the new GLocal business scenarios, for example:

12. Macro printing. 13. Smart uses. 14. Sensitive printing. 15. Printers' fabrication. 16. Multi-material 3D printing. 17. Medical advances. 18. AR, VR and 3D modeling. 19. Home printing. 20. Innovations in SMEs and SMBs.	L. Creativity-driven innovations. M. Design for Circular Economies. N. Design for developing countries. O. Design for customers' values. P. Service Design. Q. Bottom-up Design approach. R. Eco-productions. S. Design for sharing economy.	o GLocal-oriented co-development of solutions for the economic emancipation (i.e. 8+15 N+O). o Strategic co-development for the GLocal growth (i.e.19 E). o Development of human capital to empower self financeable forms of GLocal entrepreneurship (i.e. 18 S). o Support the GLocal promotion of autochthonous productions (i.e. 2 N). o Codification and exportation of identitary production techniques and skills in the GLocal markets (i.e. 20 O). o Development of context-based products and services to empower the GLocal businesses (i.e. 18 B+I). • Sustainable innovation of products, services and systems of products, for example: o Creation of context-based innovations to boost local heritage (i.e. 10 M). o Development of HCD business solutions to promote inclusive and sustainable socio-technical-economic self-sufficiency (i.e. 9+20 L+Q). o Promotion of sustainable 4.0 (i.e. 13 O+R). o Identitary development of GLocal forms of business (i.e. 14 G+L). o Sharing of know-how (i.e. 7 N). • Strategic development of economies and large-scale actions to support GLocalisms, for example: o Development of GLocal platforms to meet top-down and bottom-up needs (i.e. 4+5+6+11 F+L). o Democratization of GLocal technologies (i.e. 17+18 M+N). o Development of resilient GLocal infrastructures to support multi-level forms of business and entrepreneurships (i.e. 19+20 D+R). o Development of distributed forms of intellectual capitals (i.e. 1 H+L).

Design Opportunities here described show promising strategic design-oriented scenarios where the idea of 'Sustainable 3D Printing' can play a significant role in the creation, promotion and participative implementation of eco-friendly production processes, aware ways of consumption and new business-oriented behaviours. In particular, the results here presented are conceived to involve, where possible, all product-service's value chain. Design Opportunities are therefore intended as favorable if related to scenario-based sustainable conditions (i.e. there must be the stakeholders' will to act in a sustainable-oriented way, existing – or will to start – of green business models, etc.). Thus, information shown in Table 1 can be applied both to industrial and to non-industrial sectors.

5. CONCLUSIONS

As discussed in this paper, 3D Printing technologies are radically evolving and improving the all design activities, production processes and supply services. Since the increasing of technological advances and performance of processes are producing a sort of democratization of solutions and services – technology-push approach (Verganti, 2009) – the environmental issues linked to the printing of products and items are still less considered, while the marked demand of sustainable solutions needs and, in some cases, it drives the marked demands. In general, the issue of Sustainable Development only partially is meeting the 3D Printing domain, while in some way it is ready to act in a sustainable-oriented perspective; however, to meet the instances of the 'sustainable culture', a new idea of 'Sustainable 3D Printing' must be developed in order to produce systemic impacts and bottom-up innovations (i.e. SLOC-oriented 3D Printing) both in industry and in informal scenarios (i.e. GLocal small productions of printable items, SMBs for printed masterpieces, etc.), which are perfectly in line with the Design for Sustainability approaches. The new idea of 'Sustainable 3D Printing', if correctly understood and implemented using, for example, proper context-based technologies and aware business models, can play a significant role in the transition process toward the sustainable society. Accordingly, as the need of sustainable solutions is still high, the evolution of 3D Printing's paradigms toward network-based, hybrid PSS-based and SLOC-oriented scenarios, can surely meet the Design Research in the field of Design for Sustainability and the technology-driven research of 3D Printing industry. As shown, this study also analysed both Design for Sustainability and 3D Printing literatures to produce a new framework for the 'Sustainable 3D Printing', which is now composed by a number of promising Design Opportunities, as a part of a

more wide and holistic scenario where, in the near future, promising applications will connect Engineering, Chemistry, Materials Science, Economics, Design, etc. Finally, the Design Opportunities synthetically introduced a number of new topics and scenarios for promising applications concerning 'Sustainable 3D Printing' – if conditions of Sustainable Development are reached using competitive business models – linking current 3D Printing advances with traditional and novel Design for Sustainability's research approaches, with the idea that a holistic approach can be used, and warmly recommended, to tackle the various issues of Sustainable Development, beyond the mono-disciplinary approach.

6. DISCUSSIONS

This work can be considered relevant for both the research domains of 3D Printing and for Design for Sustainability due to it systematizes the relevant advances of both areas, proposing a their convergence toward the development of a common ground for mutual experimentations. Specifically, it is possible to identify some aspects of novelty for products, services, systems and, in general, for the culture of designers. About the products' dimension, the early insights developed in this work can meet, for example, the emerging need of new sustainable solutions made using the minimum amount of material (Rifkin, 2012; Ceschin and Gaziulusoy, 2016), as well as the number of new eco-friendly and sustainable-oriented solutions (i.e. eco-products), which now can be designed and produced – printed – using eco-aware processes and technologies now more in line with the values of contexts, networks and materials. About the services' dimension, the results developed within the Design Opportunities' framework can be further implemented to support any tangible dimension for Sustainable 3D Printing. In other word, the early data achieved in the domain of new printable products can be consolidated using new low-footprint services and intangible solutions, to empower the tangible dimension of solutions (Vezzoli, 2010; Ceschin, 2014). Consequently, the third level of development concerns the systemic dimension, as a result of the combination of both tangible and intangible applications, namely products and services. As demonstrated by SLOC, PSS and SDS, the systemic development of Sustainable 3D Printing can surely improve, as a consequence, the quality of products and services (Manzini, 2010; Gebler, 2014).

Finally, about the culture of designers, the results here achieved can be useful to develop a new design awareness, which can be used by designers, makers, entrepreneurs and stakeholders to address the future development of new proactive printable sustainable solutions for new emerging markets and countries.

CREDITS

This paper shows the early results of a research project on the role of Design for Sustainability in 3D Printing domain. While all authors have contributed in the development of results, the writing of paragraphs can be attributed to: Emilio Rossi for '4. Results', Massimo Di Nicolantonio for '3. Methodology', Paola Barcarolo for '1. Introduction', Jessica Lagatta for "6. Discussions" and Alessio D'Onofrio for 'Abstract' and '2. Aims'. Furthermore, Emilio Rossi and Massimo Di Nicolantonio equally contributed for the writing of "5. Conclusions".

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