Sustainable 3D Printing: Design Opportunities and Research Perspectives

Emilio Rossi[1,2](✉), Massimo Di Nicolantonio[2], Paola Barcarolo[3], and Jessica Lagatta[2]

[1] Emilio Rossi Design Consulting, Via Venezia 4, 66026 Ortona (CH), Italy
erossidesign@gmail.com

[2] Department of Architecture, University of Chieti-Pescara, Viale Pindaro 42, 65127 Pescara (PE), Italy
{m.dinicolantonio, jessica.lagatta}@unich.it

[3] Polytechnic Department of Engineering and Architecture, University of Udine, Via Delle Scienze 206, 33100 Udine (UD), Italy
paolabarcarolo@gmail.com

Abstract. As 3D Printing process, technologies and tools are rapidly becoming pervasive and used both in industrial and in non-industrial contexts, the risk to have new unsustainable printing processes and production's behaviours is high and, potentially, can led to the increasing of environmental emergency (un-sustainable growth). On the other hand, Design for Sustainability works, since late 80's, on the mitigation of production's environmental foot-print and, recently, on the development of socio-technical systems and distributed hybrid solutions empowering both environmental aspects and socio-economic ones. This paper investigates the new concept of Sustainable 3D Printing using recent Design for Sustainability's research theories and design approaches, in order to evaluate, and later describes, promising design opportunities and research perspectives that can be used and taken into account, simultaneously, by designers, researchers, entrepreneurs and policymakers to support the societal transition toward sustainable ways of design, production and consumption.

Keywords: 3D printing · Design for Sustainability · Sustainable scenarios · Product-Service Systems · Design research

1 Introduction

As reported in the so-called 'Brundtland Report', adopted at the UN General Assembly in 1987, the concept Sustainable Development is described as 'a development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [1]. Sustainability therefore is not an approach, it is a societal multi-dimensional long-term goal; in the idea of Sustainable Development, both environmental protection and socio-technical innovations are equally fundamental to mitigate the anthropic impacts on ecosystems at the micro- and macro-scale.

While the original idea of Sustainable Development has not changed over years, the new market demands due to both the demographic growths, the democratization of

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technologies and the rising of new fast-emerging economies, generated a radical evolution in the approach of the sustainability-related issues. This aspect has been crucially evident in the industrial production and, consequently, in Design discipline, which is intrinsically chosen to meet both end-users' needs (marker demand) and entrepreneurial competitiveness (market offer). As a part of an integrated process involving products' generation, development and distribution, Design discipline contributed in the evolution of the concept of Sustainability: from the design eco-friendly products (environmental approach) [2], to the design of context-based forms of well-being (networked approach) [3, 4] and, in last years, to the design of socio-technical systems for social innovation (systemic business approach) [5].

Years of researches and design experimentations have demonstrated that Sustainability in Design is now related to the design of sustainable forms of wellbeing, which are able to generate new forms of consumption [6]. This means that to create sustainable solutions, a significant attention must be paid on the socio-technical impacts of people's behaviors.

In the recent Industry 4.0's model, 3D Printing is an umbrella term used to describe all processes in which material is joined or solidified under computer control to create three-dimensional objects [7]. While 3D Printing was born for industrial and commercial-oriented applications, in recent years the democratization of services and the low prices in the purchasing of 3D printers generated a large number of informal and non-industrial applications (i.e. makers movement, Fab Labs, etc.). In doing so, people acquired a new awareness on their capability to produce customized products; consequently, new generation of services have been developed to support this socio-technical expansion [8] and waste reduction [9, 10].

Even though new informal 3D printing applications and productions can, in some way, be intended as new distributed socio-technical sustainable forms of low-tech production, the risk to produce unsustainable impacts on the ecosystems is still high. The main problem linked to this issue is that sustainable-oriented advances on 3D Printing technologies concern, mainly, the development of non-connected solutions – vertical approach, monodisciplinary research – for instance: eco-efficient materials (i.e. recycled biomaterials) [11], spontaneous forms of services for production (i.e. print-to-delivery services, cloud manufacturing) [12], economically efficient services (i.e. 3D Printing for education) [13], architectural solutions for housing emergency [14] and low-tech applications (i.e. DIY 3D printers) [15]. Thus, there is a discrepancy between what can be done and what is currently done in terms of Sustainable Development. A systemic approach is therefore needed to connect all existing forms of sustainable-oriented advances with the need of balancing the economic, environmental and social production of goods – horizontal approach, multidisciplinary research.

As the need of sustainable solutions is a prerogative for current society, it is believed that an expansion of current technology-centered 3D Printing approach toward multidisciplinary perspectives can expand its intrinsic potential toward new generation sustainable scenarios. Following the societal transition process toward the Sustainability, 3D Printing can become a part of new production processes and ways of thinking able to produce radical, distributed and large-scale innovations. In this perspective, this work is based on the hypothesis that current advances in Design for Sustainability theories (i.e. PSS (Product-Service Systems) [5] and SLOC Scenarios

(Small-Local-Open-Connected) [6]) can improve the quality of existing 3D Printing-related services, generating new opportunities and research challenges.

2 Aims

According to current advances in 3D Printing and Design for Sustainability of the research framework before described, this paper aims to identify new and promising open research topics to be taken into account in the near future, to rethink their impacts, to suggest potential combinations and to imagine new roles and future sustainable applications for 3D Printing. Specifically, this paper aims to:

- Produce evidences linking 3D Printing technologies and sustainable design-oriented theories, from the design point of view.
- Demonstrate the positive impacts of Design for Sustainability's theories in the advancement of 3D Printing technologies toward new generation of services and new forms of productions – Sustainable 3D Printing scenarios.
- List a number of promising design opportunities and research perspectives for Sustainable 3D Printing, obtained form a cross-fertilization process and usable for next interdisciplinary studies and applications.

3 Methodology

To meet the research's aims, the methodology phase focused the attention on the literature review of both 3D Printing emerging sustainable-oriented theories and cutting edge Design for Sustainability models. Relevant data obtained from both reviews have been used later to develop a cross-fertilization design-oriented scenario for Sustainable 3D Printing, where insights have been combined and further developed.

3.1 3D Printing's Literature Review

Sustainability-oriented 3D Printing advances follow a vertical approach (i.e. monodisciplinary research), which are the result of a 'traditional' industrial technology-push culture – see: [16, 17]. In fact, current state of the art of researches and industrial developments are mainly focused[1] on:

- Circular Economy's scenarios – i.e. recycling, low energy grids, etc. – [11–18].
- Technological improvements of production processes [11–19].
- Development of printable (bio)materials [11–13, 20–23].
- Low-cost and open-sources 3D Printing technologies services [13].
- New technological components – i.e. simplification of semifinished elements – including construction industry [24, 25].
- Innovation in engineering and engineering-related domains [25, 26].

[1] This list shows only main evidence-based advances for sustainable-oriented 3D Printing.

- Interdisciplinary applications – i.e. Inclusive Design – [27].

As shown, the main aspect related to the sustainability is linked to the environmental protection, which concerns the low-cost reduction of processes (affordability), the mitigation of the impacts on ecosystems and the compatibility of materials. Very limited applications and considerations on the economic and social aspects of Sustainable Development – 'three-legged stool' model [1] – demonstrates that environmental aspects are very easy to be taken into account and, consequently, integrated approaches considering all aspects of Sustainable Development are not always possible, or rather, are not affordable in terms of industrial production and returns of investments.

A holistic view of 3D Printing is then needed to evolve the simplistic eco-characteristics of productions, toward integrated approaches that consider all products' life cycle elements, including: material supply, design of solutions (i.e. solutions that meet both ecological aspects and socio-economic customers' needs), processes simplification, respect of workers, etc. A strategic design approach could help this transition toward sustainable printable solutions connecting, always, all domains of Sustainable Development: economics, environmental and social aspects.

3.2 Design for Sustainability's Literature Review

The review of Design for Sustainability's literature helps to understand main sustainable-oriented design approaches for creating promising sustainable solutions (i.e. mix of strategies, tools, services and products). These studies have been developed both by researchers and by research communities (i.e. [28]). While the industrial products' environmental impact is still a relevant factor for Design (i.e. cleaner production and technologies, waste minimisation, recycling approaches, eco-design, etc.), it is today not considered as sufficient to pursue the sustainable characterization of solutions; systemic approaches are more and more often preferred and considered as effective. Accordingly, the review will be mainly focused on the analysis of the three approaches that are considered as most promising for current Design Research:

- Design for Small-Local-Open-Connected Scenarios of wellbeing (SLOC).
- Design of Product-Service Systems (PSS).
- System Design for Sustainability (SDS).

As stated by Ezio Manzini [29], the only sustainable way to get out of the current worldwide financial and ecological crisis is to promote new economic models, new production systems and new ideas of wellbeing. SLOC Scenario (Small-Local-Open-Connected) is a sustainable-oriented design model developed by Manzini [29–31] where emerging global phenomena are intersected with three main innovations:

- The green revolution (and the environmentally friendly systems it makes available).
- The spread of networks (and the distributed, open, peer-to-peer organizations it generates).
- The diffusion of creativity (and the original answers to daily problems that a variety of social actors are conceiving and implementing).

SLOC Scenario is useful because it directs toward sustainable solutions indicating, in particular, that such solutions necessarily refer to the local (and the community to which this local mainly refers) and to the small (and the possibilities in terms of relationships, participation, and democracy that the human scale makes possible). 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. For example, using networks, stakeholders can operate both on small-scale, in a very effective way, and on complex and large-scale, acting as a transition actors towards a knowledge-based and sustainable idea of society.

On the other hand, Product-Service System (PSS) concept aims to minimise environmental impacts of both production and consumption. PSS is defined as 'a marketable set of products and services capable of jointly fulfilling a user's need' [32]; in this scenario the product/service ratio can vary, either in terms of function fulfilment or economic value' [33]. According to Mont [33], PSS consists of a combination of eco-designed products, reinforced by designed services at different stages of a product's life cycle, and comprising different concepts of the product use, closely involving final consumers and actors in the chain and beyond.

According to this idea, there is a significant evolution in the business models – a mitigation of environmental impacts and a high customers' satisfaction [34] – and benefits are produced both for customers and for producers. For consumers, PSS evolves the meaning of purchasing: from buying products to buying services and systems of solutions that minimise the environmental impacts of consumers' needs. For producers, PSS imposes a higher control on full life cycle process (i.e. co-design [35] and closed loop systems).

As discussed by Mont [34] and Ceschin [5–35], there are different benefits to developing a PSS for manufacturing companies. For example PSS is able:

- To increase the product's value (i.e. financial schemes, renovations, upgrades).
- To base a growth strategy on innovation in a mature industry.
- To improve relationships with consumers (i.e. new flows of information about consumers' preferences).
- To improve the total value for customers because of increased servicing and service components extend its function.
- To anticipate the implications of future take-back legislation.

In addition, the literature suggests some relevant approaches and trends towards the development of PSS, such as:

- The sale of the use of the product instead of the product itself.
- The change to a 'leasing society'.
- The substitution of goods by means of service machines.
- A repair-society instead of a throwaway society.

Finally, as described by Carlo Vezzoli [36], System Design for Sustainability (SDS) is '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'. Starting from the will to satisfy end-users' needs, the SDS's aim is to obtain a product-service that is sustainable from the environmental, social and economic point of view. SDS can be developed using the specific 'Method for System Design Sustainability' (MSDS) [36] and its key elements are:

- Customer satisfaction (satisfaction unit), intended as a 'reference'.
- Interaction between stakeholders as a 'subject';
- The Sustainability as a 'goal'.

3.3 Cross-Fertilization Scenario

The development of Design Opportunities (DO) and promising Research Perspectives for Sustainable 3D Printing (S3DP) – see 4 – has been done using a cross-fertilization innovation-oriented process [37] aimed to produce both vertical and, mostly, meaningful horizontal innovations. As a part of a design-driven innovation process (i.e. [16]), cross-fertilization has been used as a 'sustainable-oriented scenarios generator'.

As shown in the formula below (1), the new Design Opportunities (DO) are the result of a qualitative analysis developed combining main elements of 3D Printing technologies (3DP) and relevant approaches of Design for Sustainability Research (DfS).

$$DO_{(S3DP)} = 3DP \cap DfS. \quad (1)$$

4 Results

Design Opportunities and Research Perspectives here described show promising strategic design-oriented scenarios where the idea of Sustainable 3D Printing, as here proposed, 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.

Both Design Opportunities and Research Perspectives are intended as favourable 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 both in Design Opportunities and in Research Perspectives can be applied both to industrial and to non-industrial sectors.

4.1 Design Opportunities

Four main Design Opportunities ($DO_{(S3DP)}$) presented in Table 1 combine Design for Sustainability research approaches (DfS) with sustainable-oriented 3D Printing technological advances (3DP). These describe a number of new topics and scenarios for promising applications concerning Sustainable 3D Printing (if conditions of Sustainable Development have been reached using competitive business models).

Table 1. Design opportunities for sustainable 3D printing: Early research framework.

3D Printing Technological Advances (3DP)	Design for Sustainability Res. Approaches (DfS)	Design Opportunities for Sustainable 3D Printing ($DO_{(S3DP)}$ = 3DP ∩ DfS)
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 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	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) 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	• Use of local resources and values for Circular Economies and SMBs, for example: – Creation of renewable, zero impact, eco- and/or biomaterials (i.e. 1, ∩ B) – Creation of smart GLocal production networks (i.e. 7 + 9 + 20 ∩ D + I + J) – (Co-)creation and sharing of tangible and intangible resources (i.e. 7 ∩ H) – Development of B2B services for SMBs and SMEs (i.e. 4 + 6 ∩ G + S) – 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: – GLocal-oriented co-development of solutions for the economic emancipation (i.e. 8 + 15 ∩ N + O) – Strategic co-development for the GLocal growth (i.e. 19 ∩ E) – Development of human capital to empower self-financeable forms of GLocal entrepreneurship (i.e. 8 ∩ S) – Support the GLocal promotion of autochthonous productions (i.e. 2 ∩ N) – Codification and exportation of identitary production techniques and skills in the GLocal markets (i.e. 20 ∩ 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: – Creation of context-based innovations to boost local heritage (i.e. 10 ∩ M) – Development of HCD business solutions to promote inclusive and sustainable socio-technical-economic self-sufficiency (i.e. 9 + 20 ∩ L + Q) – Promotion of sustainable 4.0 (i.e. 13 ∩ O + R) – Identitary development of GLocal forms of business (i.e. 14 ∩ G + L) – Sharing of know-how (i.e. 7 ∩ N) • Strategic development of economies and large-scale actions to support GLocalisms, for example: – Development of GLocal platforms to meet top-down and bottom-up needs (i.e. 4 + 5 + 6 + 11 ∩ F + L) – Democratization of GLocal technologies (i.e. 17 + 18 ∩ M + N) – Development of resilient GLocal infrastructures to support multi-level forms of business and entrepreneurships (i.e. 19 + 20 ∩ D + R) – Development of distributed forms of intellectual capitals (i.e. 1 ∩ H + L)

4.2 Research Perspectives

Research Perspectives shown in Table 2 combine sustainable scenarios – i.e. scenarios where the idea of Sustainable Development generates social innovations, wellbeing-oriented economic models, and new forms of production systems – and relevant opportunities for Sustainable 3D Printing. The idea is to show some promising research topics and strategic views usable by designers[2] and researchers to the advancement of current state of the art in the industrial and non-industrial research.

Table 2. Research perspectives for sustainable 3D printing: Early open research insights for industrial and non-industrial future applications.

Sustainable Scenarios	Research Perspectives
1. Healthier Society	• Printable zero waste foods (i.e. [38]) • Printable tools for health monitoring (i.e. chirurgical tools) • Printable highly customizable medical tools (i.e. prosthesis) • (Just-in-place) production in emergency contexts • Advanced biodegradable packaging • Remote development of tools • Self-production of personal goods • Customizable personal everyday products • Smart printing of devices for health monitoring (i.e. IoT)
2. Social Housing	• Production of in situ semifinished or preassembled parts • Production of temporary homes for emergency contexts • Production of less-components homes • Printable solutions to mitigate the environmental impacts • Solution having fewer components • Eco-efficiency materials for construction industry • In situ customizable fabrication and personalization • Integration of multifunctional components (i.e. kitchen + infrastructures (gas, water, electricity, …) + infill walls). • Remote control of productions (i.e. BIM for 3D Printing) • Certification of printable buildings and structural elements.

(*continued*)

[2] The term ‘designer’ is here used in its general meaning: as someone able to ideate and realize a new solution, or a solution significantly better than existing ones.

Table 2. (*continued*)

Sustainable Scenarios	Research Perspectives
3. Sustainable Industrial Development	• Implementation of 4.0 paradigms (i.e. [39]). • Delocalized production and monitoring • New standards and certifications for industrial 3D Printing • From 'Just-In-Time' and 'Just-In-Place' productions to 'Only-When-Needed' behavior – production awareness • Rational manufacturing in emerging economies and developing countries (i.e. [40]) • Innovation through ubiquitous productions and knowledge sharing for 3D Printing (i.e. copyleft products, sharing of best practices, references, handbooks, etc.) • Printing of eco-materials (i.e. use of printable biopolymers) • Design of printing-driven technology optimized components (i.e. follow stress lines to concentrate materials) • Simplifications of joints and assembly for complex parts • Open industry (i.e. participative training, cooperative business models, stakeholders involvement etc.) • Shared printable production of components (i.e. licensing, production of low complex elements, etc.)
4. GLocalism's Empowerment (Global & Local Resources) (i.e. [30]).	• Small-Local-Open-Connected 3D Printing, for example: – Small-Local 3D Printing (i.e. new craftsmanship) – Small-Open 3D Printing (i.e. farms for rural stability) – Small-Connected 3D Printing (i.e. rural B2B services) – Local-Open 3D Printing (i.e. tourism productions) – Local-Connected 3D Printing (i.e. education tools) – Open-Connected 3D Printing (i.e. networked labs) • 3D Printing for transition scenarios • Context-based local-to-global 3D Printing, for example: – Promotion of local materials in 3D Printing – Promotion of traditional production techniques – Use of meaningfulness in production

(*continued*)

Table 2. (*continued*)

Sustainable Scenarios	Research Perspectives
5. Education & Skills Development	• Development of skills for new craftsmanship • Protection and enhancement of Cultural and Natural Heritage (i.e. [27–41]) • Development of tools for Education (i.e. [41]) • Improvements in Engineering and Design trainings (i.e. Design, Chemical, Mechanical, System, etc. [41])
6. Promotion of Sustainable Economies	• Development of new 3D Printing-based economies • Diversification of economies including 3D Printing-oriented technologies (i.e. ICTs, IoT, 4.0 Industry, etc. [41]) • Sustainable transition in Developing Countries (i.e. [6]) • Market implementation and investments on new infrastructures. • Investments in new knowledge-based economies • Implementation of alternative production infrastructures (i.e. using SLOC scenarios [6–31])
7. New Design	• New design of new printable solutions (i.e. [41]) • Focused Personalization (i.e. production of 80% completed products – to be personalized) • 3D Printing in everyday life of customers • Printable everyday/lifestyle products • R&D of new comfortable materials for 3D Printing • 3D Printing of objects (i.e. furniture, lighting, cloths, etc.) • Contrast of disposal personal goods (i.e. [6–31]) • Design and 3D Printing of complex systems using fewer number of components (i.e. integrated hinges) • Human Centered Design for 3D Printing
8. Interdisciplinary Topics	• A sustainable-oriented interdisciplinary topic concerning any potential Sustainable Scenarios (i.e. GLocalism, Social Innovation, Social Inclusion, etc.) not listed before

5 Conclusions

The early research results here presented and synthetically described, have shown that the concept of Sustainable 3D Printing can, potentially, produces remarkable innovations and impacts both in industry and in informal scenarios (i.e. GLocal small productions, SMBs, etc.), if correctly understood and implemented using smart technologies, aware business models, context-based resources – both tangible and intangible – and collective intelligences; this, in fact, is perfectly in line with well-known Design for Sustainability approaches – i.e. [3–5, 34, 36, 42]. As the need of sustainable solutions is still high in current society, the evolution of 3D Printing's paradigms toward network-based, hybrid and SLOC-oriented scenarios can surely meet the Design Research in the field of Design for Sustainability with the applicative potentials of 3D Printing technologies.

In particular, this study showed both Design Opportunities and Research Perspectives for the new idea of Sustainable 3D Printing, which are part of a more wide scenario where, in last years, some interesting studies are proposing original views and specific applications for Engineering, Chemistry, Materials Science, etc.

The Design Opportunities presented in 4.1 introduce a number of new topics and scenarios for promising applications concerning Sustainable 3D Printing – if conditions of Sustainable Development have been reached using competitive business models – linking current 3D Printing advances with traditional and novel Design for Sustainability 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 monodisciplinary approach.

The Research Perspectives presented in 4.2 combine sustainable scenarios – i.e. scenarios where the idea of Sustainable Development generates social innovations, wellbeing-oriented economic models, and new forms of production systems – and relevant opportunities for Sustainable 3D Printing. As a result, this research result developed promising holistic research topics and strategic views for the advancement of current state of the art in the industrial and non-industrial research.

Finally, this study can be considered relevant for both the research domain of 3D Printing and for the research domain of Design for Sustainability due to it systematizes the relevant advances of both domains, proposing a their convergence toward the development of a common ground for mutual experimentations.

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